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United States
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Municipal Environmental Research
Laboratory
Cincinnati OH 45268

EPA-600/2-78-196
December 1978

Research and Development

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LAND IMPOUNDMENT TECHNIQUES

by

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FOREWORD

The Environmental Protection Agency was created because of increasing public and government concern about the dangers of pollution to the health and welfare of the American people. Noxious air, foul water, and spoiled land are tragic testimony to the deterioration of our natural environment. The complexity of that environment and the interplay between its components require a concentrated and integrated attack on the problem.

Research and development is that necessary first step in problem solution, and it involves defining the problem, measuring its impact, and searching for solutions. The Municipal Environmental Research Laboratory develops new and improved technology and systems for preventing, treating, and managing wastewater and solid and hazardous waste pollutant discharges from municipal and community sources, for preserving and treating public drinking water supplies, and for minimizing the adverse economic, social, health, and aesthetic effects of pollution. This publication is one of the products of that research, a most vital communication link between the researcher and the user community.

Within EPA, this information will be of value to the R&D industrial program for all industries and to such groups as the Office of Solid Waste and the Office of Toxic Substances. This report will be very useful to the industry itself, since such an assembly of information is not readily available elsewhere.

Francis T. Mayo
Director
Municipal Environmental
Research Laboratory

ABSTRACT

This report presents the results of a literature search and state-of-the-art survey of liner materials utilized in land impoundment sites for the containment of seven general types of industrial wastes: (1) caustic petroleum sludge, (2) acidic steel-pickling waste, (3) electroplating sludge, (4) toxic pesticide formulations, (5) oily refinery sludge, (6) toxic pharmaceutical waste, and (7) rubber and plastic waste. The objectives of the study were to assemble the available information concerning the chemical and physical properties, cost, and field performance of various liner materials. Data obtained from the literature search were supplemented with information from various materials producers, liner manufacturers, fabricators, suppliers, installers, consultants, and trade association representatives.

In addition, the report contains an engineering analysis of the compatibility of the liner materials and the industrial wastes of interest. From this analysis, preliminary recommendations are made concerning the suitability of the liner materials for containing the specified industrial wastes.

This report was submitted in fulfillment of Grant No. R-803585 by Exxon Research and Engineering Company under the sponsorship of the U.S. Environmental Protection Agency. Work was originally completed as of May 31, 1975, but the report has been edited and revised by Matrecon, Inc., to update the conclusions (1978) by reflecting the findings of ongoing work, particularly in the two research contracts, EPA 68-03-2134 and EPA 68-03-2173. Additional references have been added to the bibliography as well.

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SECTION 1

INTRODUCTION

This report describes the results of a state-of-the-art study of various liner materials utilized in land impoundment sites for the containment of seven general types of industrial waste. The objectives of the study were to assemble information concerning the chemical and physical properties, cost, and field performance of various liner materials as well as any other pertinent data to determine or estimate their suitability for containing specific, representative industrial wastes. In addition, an engineering evaluation was conducted so that recommendations could be made concerning the compatibility of these liner materials and the industrial wastes specified. Ultimately, these evaluations contribute to the determination of preferential liner materials that can be used in specific land impoundment situations.

Information was sought concerning the following commercially available liner materials:

1. Flexible membrane liners and fabric-reinforced (nylon, dacron, glass fiber) flexible membrane liners:
 - a. Polyvinylchloride (PVC)
 - b. Polyethylene (PE)
 - c. Polypropylene
 - d. Butyl rubber
 - e. Chlorinated polyethylene (CPE)
 - f. Ethylene propylene rubber (EPDM)
 - g. Chlorosulfonated polyethylene (Hypalon)
 - h. Neoprene
2. Admixed materials:
 - a. Asphalt concrete
 - b. Soil cement
 - c. Soil asphalt
 - d. Sprayed asphalt membranes
3. Soil sealants:
 - a. Rubber latex
 - b. Bituminous sealcoat
4. Natural soil systems:
 - a. Soil bentonite
 - b. Compacted clays

The general categories of industrial wastes considered for containment in these liner materials were:

1. Caustic petroleum sludge
2. Acidic steel-pickling waste
3. Heavy-metal-bearing electroplating sludge
4. Toxic pesticide-formulation waste
5. Oily refinery sludge
6. Toxic pharmaceutical waste
7. Wastes from rubber and plastics industries

Information used in the preparation of this report was obtained from extensive literature searches; trade and industry associations; raw materials producers; manufacturers; fabricators, suppliers, and installers of liners; and interviews and discussions with various consultants, industry personnel, and trade association representatives.

SECTION 2

CONCLUSIONS

Based on the information gathered during the course of this study, the following conclusions have been formulated:

1. The literature contains few meaningful engineering and performance data on which to base an engineering analysis of lined land impoundment sites that contain the industrial wastes of interest. Most of the literature referred to commercial-type articles describing potable water installations, sewage lagoons, and brine evaporating ponds; or it simply mentioned the existence of industrial waste retention ponds without presenting any engineering or performance data.
2. The liner materials have been characterized to some extent in the literature--most notably in information available from the various manufacturers, fabricators, suppliers, installers, and trade associations. Manufacturers and fabricators in particular do make available information concerning the chemical, physical, and mechanical properties of the specific materials that they either manufacture or formulate. Therefore, substantial information is available on the chemical and physical properties, material costs, and installation methods and costs.
3. In a number of instances, information concerning the complete characterization of a specific or representative industrial waste in terms of major chemical components and the concentrations of the components appeared either to be unavailable or reported in terms such as biochemical oxygen demand (BOD₅), chemical oxygen demand (COD), total organic carbon (TOC), etc. Such characterizations do not supply sufficient information to make realistic liner/waste compatibility predictions. Thus the analyses presented in Section 9 are at best approximations based on the best available chemical characterization data.
4. The selection of a liner material for an impoundment site that will contain one of the representative industrial wastes listed in Table 1 should involve the following considerations:
 - a. The liner material should satisfactorily resist attack from all chemicals (solvents, oils, greases, etc.), ozone, ultraviolet radiation, soil bacteria, mold, fungus, and vegetation to which it will be exposed. Resistance can be determined by laboratory testing of the liner material in the industrial waste that the liner will contain.
 - b. The liner material should have ample weather resistance to withstand the stresses associated with wetting and drying, freezing and thawing,

and periodic shifts of the earth as dictated by the geographic location of the impoundment site.

- c. The liner material should have adequate physical properties to withstand the stresses of installation and damage from machinery or equipment.
- d. The liner material should resist laceration, abrasion, and puncture from any matter that may be found in the fluids that it will contain.
- e. The liner material should be easily repairable at any time during its life (particularly when repairs are feasible), and it should be the most economical material that can adequately fill the specific application.
- f. The liner material should be properly installed. Improper installation of even the best material will defeat the purpose of the lining.
- g. To provide longer life and protection against mechanical damage and weathering, all flexible membrane liner materials, both exposable and unexposable, should be covered, if possible, with a layer of sand or fine-textured soil.
- h. Proper filling and maintenance of the liner and impoundment site should be practiced.

TABLE 1. LINER/INDUSTRIAL WASTE COMPATIBILITIES

Liner Material	Industrial Waste*						
	Caustic Petroleum Sludge	Acidic Steel-Pickling Waste	Electroplating Sludge	Toxic Pesticide Formulations	Oily Refinery Sludge	Toxic Pharmaceutical Waste	Rubber and Plastic
Polyvinylchloride (oil resistant)	G	F	F	G	G	G	G
Polyethylene	G	F	F	G	F	G	G
Polypropylene	G	G	G	G	G	G	G
Butyl Rubber	G	G	G	F	P	F	G
Chlorinated Polyethylene	G	F	F	F	P	F	G
Ethylene Propylene Rubber	G	G	G	F	P	F	G
Hypalon	G	G	G	F	P	F	G
Asphalt Concrete	F	F	F	F	P	F	G
Soil Cement	F	P	P	G	G	G	G
Soil Asphalt	F	P	P	F	P	F	G
Asphalt Membranes	F	F	F	F	P	F	G
Soil Bentonite (Saline Seal)	P	P	P	G	G	G	G
Compacted Clays	P	P	P	G	G	G	G

*P=poor, F=fair, G=good.

SECTION 3

RECOMMENDATIONS

1. Perhaps the most important sources of engineering and performance data on liner materials for industrial wastes are the installers of the liner materials and the owners of the lined industrial waste ponds. During the course of this study, contact was made with a number of installers. Response to requests for specific information was very poor, probably because of the time and manpower required to assemble the information requested. Installers should therefore be contacted again to determine if they have been responsible for constructing impoundment sites that contain the industrial wastes of interest. Information requests should then be limited to items such as: (a) location of the installation, (b) owner of the installation site, and (c) type of industrial waste contained. Subsequent field trips to the installation site and discussion with the owner(s) of the site would probably result in the development of a substantial number of case histories on the liner materials already utilized in impoundment sites and on the industrial wastes contained.
2. Since the industrial wastes in each of the categories of interest are generally composed of a wide variety of chemical constituents, a more complete description of the industrial waste should be obtained by periodically requesting all industries that generate these wastes to submit detailed analyses of all waste streams discharged from their plants. Convenient forms should be designed to permit computer logging, retrieval, and analysis of the submitted data. The important analytical parameters should be specified to insure that the manufacturer is aware of the composition of the waste discharge and the potential each component has for producing environmental stress.
3. To assure the ultimate success and maximum performance of industrial waste impoundment sites, different lining materials must be tested with the individual industrial wastes of interest. Factors to be considered should include liner deterioration upon prolonged contact with the industrial waste of interest and alterations in the permeability of liner material to the waste over time.

SECTION 4

FLEXIBLE MEMBRANE LINERS FOR IMPOUNDMENT SITES

INTRODUCTION

Liner materials for impoundment sites that contain industrial waste should be: (1) impermeable to wastes, (2) durable, (3) flexible over a wide range of temperatures, (4) resistant to chemical, biological, and mechanical damage, weathering, and deterioration, (5) low in cost, and (6) easy to install.

Traditionally, ponds, pits, lagoons, and reservoirs that have been used for waste disposal, brine evaporation, potable water storage, drilling mud, and industrial waste storage have often been lined to prevent the excessive seepage of liquids into the ground. Clay or bentonite, wood, concrete, gypsum, asphalt, and metal linings have been used for many years.¹ Some of these materials do not possess all of the desired properties listed above. More recently, however, a different class of impervious lining materials has been developed--flexible synthetic membranes.

The most important advantages of flexible synthetic membrane liners for the containment of industrial waste are their ability to contain a wide variety of fluids with a minimum of loss from permeation and seepage, their high resistance to chemical and bacterial deterioration, and their relative ease and economy of installation and maintenance.

Major disadvantages include the relative vulnerability of some liners to ozone and ultraviolet deterioration as compared with hard surface liners.^{1,2} Their ability to withstand the stresses of heavy machinery is limited compared with concrete or asphalt. Also, they are comparatively susceptible to laceration, abrasion, and puncture from sharp objects such as metal chips, stones, tree roots, etc. Some membrane materials are prone to crack and crease at extremely low temperatures and to stretch and distort at extremely high temperatures.^{1,2}

FLEXIBLE POLYMERIC SYNTHETIC MEMBRANES

A number of synthetic lining materials based on rubbers and plastics are currently on the market to suit different purposes and conditions.

Variations in the formulations of both types of materials can result in liners that will be better suited to a specific application than other liners

of the same polymeric material. For example, there are several producers of polyvinylchloride (PVC), one of the widely used polymers in the manufacture of membrane liners. These producers sell the basic PVC to liner manufacturers who add various materials such as plasticizers, resins, fungicides, biocides, etc. to achieve specific properties. They process the PVC by rolling or calendering the compounded PVC into large sheets, which are joined or seamed into larger sections and ultimately sold to suppliers and/or installers. The chemical and physical properties of the resulting sheet material can therefore differ markedly from those of the original base polymer.

Flexible membrane liners can be classified as exposable and unexposable. Exposable membranes are formulated from materials that resist ozone and ultraviolet exposure for long periods of time. In the exposable materials category are the synthetic rubbers: butyl (isobutylene isoprene rubber), EPDM (ethylene propylene rubber), Hypalon (chlorosulfonated polyethylene), and neoprene (chloroprene rubber). Unexposable membranes include PVC (polyvinylchloride), polyethylene, and polypropylene. While these membranes do not resist ozone and ultraviolet attack as well as exposable membranes, they can be expected to provide satisfactory service in many applications, particularly if covered by a protective layer of soil.^{1,3} The service life of most exposable liners can be expected to range from 20 to 25 years or longer under normal atmospheric exposure, while unexposable liners could only be expected to perform satisfactorily for 10 to 15 years under similar conditions.^{1,3}

Designation as exposable or unexposable does not necessarily indicate that one group or the other has superior physical properties for all applications. An unexposable liner may have chemical resistance qualities that would adapt to a specific application as well as or better than an exposable material. The typical properties of these materials are discussed as follows and outlined in Table 2. Additional specific chemical resistance data for some liner materials are shown in Tables 3 through 9. Note that severe chemical attack of the liner material results in dramatic loss in the liner's physical properties. In an impoundment site, such dramatic losses, particularly in tensile strength, can result in failure of the liner.

PROPERTY PROFILES OF MATERIALS USED IN LINER MANUFACTURE

The following are typical property profiles of some of the more commonly used polymeric liner materials. These basic materials may be used by more than one manufacturer to produce a variety of trade-named liners. Also, each manufacturer may incorporate variations of these materials, such as added plasticizers for greater flexibility, scrim to increase tensile strength, and a variety of resins to increase resistance to specific chemicals or to improve impermeability. It is therefore very important that considerations in the selection of a flexible membrane liner for an impoundment site that will contain industrial waste begin with the basic materials.

Butyl

Butyl is a highly reliable synthetic rubber with more than 20 years of field service in the storage of potable water. Butyl rubber has good resistance

TABLE 2. GENERAL PROPERTIES OF FLEXIBLE MEMBRANE LINER MATERIALS*

Property	Polyethylene		Polyvinyl Chloride [#]	Chlorinated Polyethylene	Polypropylene	Butyl Rubber	Hypalon	Ethylene-Propylene Rubber (EPM)
	Low Density	High Density						
Specific Gravity	0.92-0.94	0.94-0.96	1.24-1.30	1.35-1.39	0.9-0.91	0.92-1.25	1.4-1.5	1.15-1.21
Tensile Strength, psi	1,300-2,500	2,400-4,800	2,500-3,500	1,800 min	4,000-32,000	1,000-4,000	1,000-2,000	1,300-1,500
Elongation, %	200-800	10-650	250-350	375-575	40-400	300 min	300-500	300 min
Shore "A" Hardness	@	@	65-75	65-75		45-80	55-95	50-70
Operating Temperature Range, F	-70 to 180	-70 to 240	-60 to 200	-40 to 200	-60 to 220	-50 to 325	-45 to 200	-75 to 300
Resistance to Acids	P-G	G	G-E	G-E	G-E	G	G	G-E
Resistance to Bases	G-E	G-E	G-E	G-E	G-E	G	G-E	G-E
Resistance to Oxygenated Solvents	P-G	P-G	G	P	P	G-E	G	G-E
Resistance to Aromatic and Halogenated Solvents	F-G	F-G	G	P	G	P	F	P
Resistance to Aliphatic (Petroleum) Solvents	F-G	F-G	G	G	G	P	G	P
Water Vapor Permeability, perm-mils	3-14	1.8-2.2	3-18	0.04-0.048	0.25-1.0	0.15	2.0	2.0
Weatherability	P-w/o black	P-w/o black	P-F	E	P-w/o black	G	E	E
Time to Crack, hr	900	300	No crack to 2,500	No effect to 4,000	100	No effect after 2,500	No effect after 1,000	No effect after 1,000
Time to Chalk, hr	No effect to 2,500	600	300	No effect to 4,000	600	No effect after 2,500	No effect after 1,000	No effect after 1,000
Time to Fade, hr	300	300	100	No effect to 4,000	900	No effect after 2,500	No effect after 1,000	No effect after 1,000

*Adapted from Reference 1.

#Plasticized PVC.

@Data not shown were unavailable. P=poor, F=fair, G=good, E=excellent. ASTM test methods for various properties: specific gravity, D-751; tensile strength, D-97-61T; elongation, D-412-61T or D-882; shore "A" hardness, D-676-59T; water vapor permeability, E-96-66.

TABLE 3. CHEMICAL RESISTANCE OF VARIOUS POND LINERS TO 100%

ETHYL ALCOHOL*#

Property	Time (days)	Vina- liner (PVC)	Vina- liner, Oil Resistant	Poly- liner (CPE)	Hydro- liner (Hypalon)	Dri- liner (Butyl Rubber)
Tensile Strength (psi)@	0	2281	2610	1649	1167	869
	7	-2.8	-11.2	-17.5	-21.8	-15.5
	28	-0.5	-5.2	-18.9	12.5	-18.0
100% Modulus (psi)@	0	1124	1406	527	433	211
	7	14.8	-22.0	70.4	-18.9	-11.4
	28	46.0	-5.3	74.0	-12.7	-11.8
Ultimate Elongation (%)@	0	425	404	651	1008	552
	7	2.1	12.4	16.7	-7.4	-10.3
	28	-6.8	7.9	2.1	-24.6	-10.7
Graves Tear (lb/in.)	0	234	310	183	230	156
	7	38	-4	-19	-17	-9
	28	54	-14	-18	-10	-2
Weight Change (%):†						
Absorption	7	-11.4	-2.4	1.1	1.7	-0.6
	28	-15.2	-6.9	1.4	3.5	-0.9
Extraction	7	-16.1	-8.8	-0.3	-0.4	-0.8
	28	-19.2	-12.1	-0.5	-0.4	-2.2

*Goodyear technical literature.

#All property values for Days 7 and 28 are expressed as the percent change from the value on Day 0. All specimens were 30 gauge (mil) except Driliner, which was 60.

@ASTM Test D882 (Method A) was used, but the rate of travel was 12 in./min instead of 20 in./min. All samples were blotted dry and brought to room temperature before being tested.

+Samples were dried for 6 hr at 158 F, for 1 hr at 212 F, and for 16 hr at room temperature before being tested.

TABLE 4. CHEMICAL RESISTANCE OF OIL-RESISTANT TYPE J11B PVC*

Factor #	Original Properties			Hexane	Ethanol	Glacial
	L	T				
Time (days)	--	--		28	28	28
Temperature of Test	--	--		@	@	@
Volume Change (%)	--	--		1.38	-10.91	-8.30
Weight Change (%)	--	--		-3.20	-9.09	-7.31
Elongation (%)	370	350		400	410	390
Modulus 100%	1800	1600		930	1270	2090
Tensile (psi)	3380	2930		2380	2350	2490
Hardness Change (pts.)	--	--		-8	+2	+8

*Goodyear technical literature.

#All age testing in transverse direction only.

@Room temperature.

TABLE 5. FORMULATIONS AND PHYSICAL PROPERTIES FOR TYPICAL
VULCANIZED COMPOUNDS OF SEVERAL COMMON ELASTOMERS*

Polymer Type	Butyl #	Intermediate Unsaturation	Butyl #	Chlorinated Butyl	EPDM	EPDM #	EPDM# (Highly loaded)	Chlorosulfonated Polyethylene
Grade	Butyl #	Intermediate Unsaturation	Low Unsaturation	Chlorobutyl 1066	Vistalon 404	High Mooney Viscosity	High Mooney Viscosity	Hypalon 40
Compounds:								
Polymer	100		100	100	100	100	100	100
SRF Black	50		50	50	50	50	50	50
MPC Black	20		20	20	20	20	20	20
FEF Black	--		--	--	--	--	--	--
Flexon 765 Oil	5		5	5	5	25	200	5
Flexon 640 Oil	--		--	--	--	--	--	--
Flexon 580 Oil	--		--	--	--	--	--	--
Zinc Oxide ⁺	5		5	5	5	5	100	5
Stearic Acid	1.0		1.0	1.0	1.0	1.0	5	--
Magnesium Oxide	--		--	--	--	--	1.0	--
Cure Systems:								
Di-Cup 40 HAF	--		--	--	7.0	--	--	--
Sulfur	1.5		2.0	1.25	0.3	1.5	1.5	--
Accelerators**								
TDADC 1.5	1.5	TDADC 2.0	2.0	DPTTS 1.25		1.5	1.5	DPTTS 1.0
MBTS 1.0	1.0	MBTS 1.0	1.0			0.5	0.5	MBTS 0.5
		ZBDC 1.0	1.0					PbO 20
Polymer, wt. %	53.76		53.19	53.90	53.11	48.90	24.42	54.49
Cure Time at 320 F, min	30		30	30	30	30	30	20

See footnotes at end of table.

TABLE 5 (continued)

Polymer Type	# Butyl	# Intermediate Unsaturation	Low Unsaturation	# Butyl	Chlorinated Butyl	EPM	EPDM #		Chlorosul- fonated Polyethylene @
							Highly loaded	High Mooney Viscosity	
Grade									
Original Physical Properties									
Hardness, Shore A	67		62		60	58	63	78	80
Tensile Strength psi	1660		1860		1980	2030	2170	1400	3590
Elongation, %	510		700		420	520	350	190	210

* Exxon Elastomers/Chemical Resistance Handbook.

Exxon elastomers conforming to the generic polymer classifications listed above are:

Butyl rubber, intermediate unsaturation Exxon butyl 268
Butyl rubber, low unsaturation Exxon butyl 065
EPDM, high Mooney viscosity Vistalon 4608

@ Generally formulated without curative when used in manufacture of liners.

+ Zinc oxide is added with the curatives in the Chlorobutyl and polychloroprene compounds

** Abbreviations:

DPTTS.....Dipentamethylenethiuram tetrasulfide
MBTS.....Benzothiazyl disulfide
PbO.....Lead oxide
TDEDC.....Tellurium diethyldithiocarbamate
TMTDS.....Tetramethylthiuram disulfide
ZDBDC.....Zinc dibutyldithiocarbamate

TABLE 6. TECHNICAL DATA - BUTYL RUBBER SHEETING*

Impermeability. The water permeability factor for Butyl rubber is 0.119 perms per mil thickness. If Butyl is assigned an index of 1.0, other materials have these relative values:

Butyl	1.0
Polyethylene	1.9
Polyvinylchloride (plasticized)	59.0

Water vapor transmission

Material	Thickness	Permeance
	(in.)	(perm or grain/hr x sq ft x in. Hg)
Polyvinylchloride Sheeting	0.055	0.11
Commercial Butyl Sheeting	0.063	0.00

(Test CR 67-16, Pennsylvania State University)

Flexibility. Functional over a temperature range of 20 to 250 F; does not become stiff or brittle with age.

Elasticity. Will elongate 300% min. and recover over the functional temp.

Durability. Resistant to tearing, flex cracking, and abrasion. Concrete is often poured directly over membrane, exercising only normal precaution against equipment damage. Slip sheets should be used in concrete/asphalt sandwich construction. Should membrane be punctured, it may be cold patched just as a tire innertube is repaired.

Age resistance. Outdoor exposure in water management use by the U.S. Dept. of Agriculture shows no evidence of degradation after 20 years of service.

Life expectancy. 20 years and more, based upon known data.

Weight per 100 ft² (\pm 2 lb) 38 lb (1/16 in. thick).

Coefficient of lineal expansion. 0.65×10^{-4} per degree F.

Coefficient of heat transfer. 2.15 BTU/(hr) (ft²) (°F/in.)

Precaution. When splice areas are cleaned with solvent, prolonged contact with skin and inhalation of the vapors are to be avoided. The solvent used for cleaning and the solvent cement must be allowed to evaporate before the joint is closed and rolled. The time required to do this will vary with humidity and temperature, but it is necessary to prevent blistered and, consequently, weak joint structures. Excess or the wrong solvent can wrinkle sheeting and inhibit good splicing.

Butyl rubber is not recommended for use in prolonged contact with gasoline or other petroleum-based solvents.

Installed costs are related to project design, but depending upon locality and thickness specified, can vary from \$.40 to \$.80/ft² in simple application. Remedial work, special shapes, and extraordinary conditions (prefabricated fittings, large number of openings, pipe or conduits to flash, etc.) could increase installed cost to near \$1.00/ft².

*Exxon Chemical Company technical literature.

TABLE 7. CHEMICAL RESISTANCE OF COMPOUND BASED ON INTERMEDIATE
UNSATURATION BUTYL RUBBER[#]

Chemical	Volume Change (%)	Tensile Strength Retained (%)	Elongation Retained (%)	Hardness Change (Pts.)	Surface Condition
INORGANIC ACIDS					
Boric Acid (10%)	-1.95	98.8	106.5	+3	Tacky
Chlorosulfonic Acid (10%)	Disintegrated				
Chromic Acid (10%)	+20.2	56.6	77.8	-10	Tacky
Chromic Acid (Conc.)	+49.6	5.42	12.3	-21	V. Tacky
Hydrochloric Acid (10%)	+0.37	104.8	102.0	+2	Tacky
Hydrochloric Acid (Conc.)	+11.2	56.0	88.8	-11	Sl. Tacky
Hydrofluoric Acid (Conc.)	+2.18	90.4	67.2	0	Sl. Tacky
Nitric Acid (10%)	+1.64	101.2	101.4	0	V. Tacky
Nitric Acid (Conc.)	Disintegrated				
Phosphoric Acid (Conc.)	+0.11	98.8	101.4	+3	Tacky
Sulfuric Acid (10%)	-0.12	95.2	95.5	+4	Tacky
Sulfuric Acid (Conc.)	Disintegrated				
INORGANIC BASES					
Ammonium Hydroxide (10%)	+5.88	106.0	96.1	-1	Unchanged
Ammonium Hydroxide (Conc.)	+7.39	101.2	89.6	-3	Sl. Tacky
Barium Hydroxide (Conc.)	+1.02	100.6	99.4	+3	Unchanged
Calcium Hydroxide (10%)	+1.05	96.4	98.6	+3	Unchanged
Potassium Hydroxide (10%)	+0.23	100.0	96.1	+3	Unchanged
Sodium Hydroxide (10%)	+0.93	104.8	99.4	+1	Unchanged
Sodium Hydroxide (Conc.)	1.77	104.8	101.4	-4	Unchanged
INORGANIC SALTS (25% Solutions)					
Aluminum Chloride	+0.34	98.2	97.5	+2	Sl. Tacky
Aluminum Sulfate	+1.34	103.6	105.3	+3	Unchanged
Ammonium Chloride	+0.12	95.2	99.4	+3	Sl. Tacky
Ammonium Nitrate	+0.13	98.2	99.4	+3	Sl. Tacky
Ammonium Phosphate	+1.03	101.8	103.9	+3	Sl. Tacky

*Exxon Elastomers/Chemical Resistance Handbook.

[#]Twelve-month immersion at 75 F ± 5°.

TABLE 7 (continued)

Chemical	Volume Change (%)	Tensile Strength Retained (%)	Elongation Retained (%)	Hardness Change (Pts.)	Surface Condition
Barium Chloride	+0.47	104.8	105.9	+4	Unchanged
Barium Sulfide	+0.51	98.2	91.6	+2	Unchanged
Calcium Chloride	+1.55	95.8	94.1	+1	Unchanged
Calcium Hypochlorite	+1.82	107.8	107.8	-1	Sl. Tacky
Cupric Chloride	+0.13	94.0	96.1	+4	Sl. Tacky
Cupric Sulfate	+1.80	96.4	99.4	+4	Unchanged
Ferric Chloride	+0.44	98.8	98.0	+3	Unchanged
Ferric Nitrate	+1.25	93.4	98.0	+1	Tacky
Ferrous Sulfate	+0.81	97.0	95.5	+3	Unchanged
Magnesium Chloride	+0.38	94.0	96.7	+3	Unchanged
Magnesium Sulfate	+0.69	94.6	96.7	+4	Unchanged
Nickel Sulfate	+0.11	94.6	99.4	+3	Unchanged
Potassium Chloride	+0.56	98.8	100.0	+1	Unchanged
Potassium Permanganate	+8.34	90.7	87.7	-3	Brittle
Potassium Bisulfite	+7.80	113.3	102.0	-4	Unchanged
Potassium Dichromate	+0.63	98.8	99.4	+3	Unchanged
Sodium Borate (Borax)	+0.73	100.6	103.9	+3	Unchanged
Sodium Bicarbonate	+0.12	98.6	100.0	+2	Unchanged
Sodium Chloride	-0.99	93.6	96.7	+3	Unchanged
Zinc Chloride	+0.23	98.2	100.0	+3	Sl. Tacky
Zinc Nitrate	+0.24	93.6	94.7	+4	Sl. Tacky
ORGANIC ACIDS					
Acetic Acid (10%)	+5.63	103.0	103.9	-1	Sl. Tacky
Acetic Acid (Glacial)	+10.7	88.6	92.2	-9	Sl. Tacky
Chloracetic Acid (10%)	+5.45	133.1	99.0	-1	Sl. Tacky
Citric Acid (10%)	+0.38	98.8	101.4	+3	Sl. Tacky
Formic Acid (10%)	+4.15	107.2	105.9	+2	Sl. Tacky
Lactic Acid (10%)	+0.45	98.8	100.0	+2	Sl. Tacky
Oleic Acid (100%)	+95.7	45.8	59.4	-27	Unchanged
Oxalic Acid (10%)	+0.12	105.4	104.9	+4	Sl. Tacky
Phenol (10%)	+7.35	115.1	112.4	-11	Sl. Tacky
Phenol (100%)	+4.50	98.8	109.8	-14	Sl. Tacky
Picric Acid (10%)	+2.07	101.2	99.4	+2	Sl. Tacky
Stearic Acid (100%)	+18.6	108.4	108.4	+2	Unchanged
Tannic Acid (10%)	1.05	100.0	96.1	-1	Sl. Tacky
Tartaric Acid (10%)	+1.08	100.6	103.9	+3	Tacky

TABLE 7 (continued)

Chemical	Volume Change (%)	Tensile Strength Retained (%)	Elongation Retained (%)	Hardness Change (Pts.)	Surface Condition
ALCOHOLS					
Benzyl Alcohol	+2.79	104.8	103.9	-8	Sl. Tacky
Ethyl Alcohol	+0.89	94.0	96.1	-2	Sl. Tacky
Isopropyl Alcohol	+1.53	92.2	96.1	-2	Sl. Tacky
Methyl Alcohol	+1.64	97.6	96.1	-2	Sl. Tacky
Ethylene Glycol	-0.36	94.6	92.2	+4	Sl. Tacky
Glycerol	+1.26	96.2	89.6	+2	Unchanged
1-Hexanol	+6.60	84.3	96.7	-11	Sl. Tacky
Resorcinol	+12.0	108.4	99.4	+1	Sl. Tacky
ALDEHYDES					
Benzaldehyde	+7.28	92.2	98.6	-13	Sl. Tacky
Butyraldehyde	+17.4	91.6	102.6	-18	Unchanged
Furfural	+5.34	103.6	103.3	-9	Tacky
AMINES					
Aniline	+7.33	98.8	103.9	-13	Unchanged
Triethanolamine	+0.77	94.0	90.2	+3	Sl. Tacky
UDMH	+7.00	58.4	77.8	-9	Unchanged
ESTERS					
Amyl Acetate	+45.7	39.8	48.4	-24	Unchanged
Dibutyl Sebacate	+19.3	85.5	103.3	-17	Unchanged
Diethyl Phthalate	+9.13	104.8	109.2	-12	Sl. Tacky
Ethyl Acetate	+8.75	78.3	88.2	-12	Unchanged
Tricresyl Phosphate	+0.49	101.8	102.6	+2	Tacky
ETHERS					
Dibenzyl Ether	+9.56	106.6	103.9	-13	Unchanged
Diethylene Glycol Mono- butyl Ether	+3.85	96.4	106.5	-10	Unchanged
Ethyl Ether	+60.2	31.3	35.3	-27	Unchanged
Ethylene Glycol Monoethyl Ether	+4.35	101.2	103.9	-7	Sl. Tacky

TABLE 7 (continued)

Chemical	Volume Change (%)	Tensile Strength Retained (%)	Elongation Retained (%)	Hardness Change (Pts.)	Surface Condition
HYDROCARBONS					
Benzene	+84.0	20.5	26.9	-30	Unchanged
Cyclohexane	+218.5	16.3	17.1	-32	Sl. Tacky
Ethylbenzene	+142.9	21.7	24.9	-32	Unchanged
Heptane	+142.0	19.3	21.0	-30	Sl. Tacky
Hexane	+125.5	21.1	23.5	-28	Sl. Tacky
Naphthalene	+41.9	89.2	79.0	+2	Sl. Tacky
Toluene	+128.5	18.7	26.1	-31	Sl. Tacky
Xylene	+142.5	19.9	21.6	-31	Sl. Tacky
HALOGENATED HYDROCARBONS					
Benzyl Chloride	+26.1	56.0	79.8	-21	Tacky
Bromobenzene	+118.0	22.9	26.1	-32	Sl. Tacky
Carbon Tetrachloride	+207.1	19.9	19.6	-32	Unchanged
Chloroform	+169.5	19.3	22.2	-33	Sl. Tacky
Ethylene Dichloride	+25.8	52.4	62.7	-18	Sl. Tacky
Perchloroethylene	+200.5	16.3	18.2	-33	Unchanged
OTHER SUBSTITUTED					
HYDROCARBONS					
Carbon Disulfide	+87.0	16.9	21.0	-31	Sl. Tacky
Nitrobenzene	+3.35	94.6	101.4	-11	Tacky
KETONES					
Acetone	+6.07	86.7	90.8	-8	Sl. Tacky
Methyl Ethyl Ketone	+8.60	83.1	88.8	-11	Sl. Tacky
Methyl Isobutyl Ketone	+22.0	56.6	75.1	-17	Sl. Tacky
Lestoil (1%)	+3.34	101.2	105.3	-1	Sl. Tacky
Lux Flakes (1%)	+1.53	101.8	100.6	+3	Unchanged
Rinse Dry (1%)	+0.96	98.8	105.3	+3	Unchanged
Rinse Dry (Conc.)	-0.74	97.6	98.0	+4	Sl. Tacky
Tide (1%)	+1.77	100.7	99.0	+3	Tacky

TABLE 7 (continued)

Chemical	Volume Change (%)	Tensile Strength Retained (%)	Elongation Retained (%)	Hardness Change (Pts.)	Surface Condition
OILS & FUELS					
A.S.T.M. No. 1 Oil	+45.8	43.4	56.9	-23	Unchanged
A.S.T.M. No. 2 Oil	+50.6	50.0	54.3	-22	Sl. Tacky
A.S.T.M. No. 3 Oil	+151.8	31.3	30.0	-32	Unchanged
A.S.T.M. Fuel A	+128.4	22.9	24.2	-29	Unchanged
A.S.T.M. Fuel B	+156.1	13.9	22.9	-32	Sl. Tacky
A.S.T.M. Fuel C	+140.0	18.1	21.0	-3	Sl. Tacky
Heating Fuel Oil	+176.0	20.5	22.9	-33	Unchanged
Jet Aircraft Engine Oil	+44.7	54.2	77.8	-23	Unchanged
Kerosine	+139.8	18.1	20.2	-32	Unchanged
AUTOMOTIVE PRODUCTS					
Chassis Grease	+53.6	38.6	43.1	-26	Unchanged
Motor Oil (10W-30)	+149.8	32.5	38.6	-33	Unchanged
Gasoline (RON 94)	+160.9	17.5	21.0	-34	Sl. Tacky
Gasoline (RON 99)	+183.4	18.7	21.6	-31	Sl. Tacky
Gasoline (RON 10-)	+203.7	17.5	21.0	-36	Sl. Tacky
Gasoline, Unleaded	+151.7	18.1	19.6	-33	Sl. Tacky
HYDRAULIC FLUIDS					
Oronite 8200	+13.7	101.8	104.5	-9	Unchanged
Pydraul F-9	+11.2	103.0	110.4	-10	Tacky
Pydraul 60	+6.70	104.8	106.5	-6	Tacky
Skydrol	+7.30	106.6	110.4	-7	Sl. Tacky
Skydrol 500	+3.37	110.2	110.4	-10	Sl. Tacky

TABLE 8. CHEMICAL RESISTANCE OF VULCANIZED CHLOROSULFONATED POLYETHYLENE COMPOUND^{*#}

Chemical	Volume Change (%)	Tensile Strength Retained (%)	Elongation Retained (%)	Hardness Change (Pts.)	Surface Condition
Aniline	+71.8	26.2	64.3	-29	Unchanged
A.S.T.M. No. 1 Oil	+0.59	108.6	95.2	+2	Unchanged
A.S.T.M. No. 3 Oil	+40.3	72.4	75.9	-12	Unchanged
Benzaldehyde	+119.8	24.5	37.2	-21	Unchanged
Dioctyl Phthalate	+110.5	39.8	43.5	-20	Unchanged
Ethyl Alcohol	+5.53	101.7	91.8	-11	Sl. Tacky
Ethyl Ether	+47.8	33.9	58.0	-19	Tacky
Gasoline (RON 99)	+51.8	32.3	51.7	-19	Tacky
Hexane	+25.0	54.6	66.2	-11	Unchanged
Hydrochloric Acid (10%)	+16.1	114.2	90.3	+4	Unchanged
Methyl Ethyl Ketone	+86.0	28.1	42.0	-20	Unchanged
Perchloroethylene	+105.7	24.5	37.2	-20	Unchanged
Potassium Permanganate (25%)	+8.83	114.2	87.0	+1	Sl. Brittle
Sodium Chloride (25%)	+1.03	115.9	93.2	+4	Unchanged
Sodium Hydroxide (10%)	+1.52	110.3	90.3	+4	Unchanged
Toluene	+188.0	24.5	35.3	-20	Sl. Tacky

*Exxon Elastomers/Chemical Resistance Handbook. Vulcanized black compound containing 54.5% polymer.

#Twelve-month immersion at 75 ± 5°.

TABLE 9. CHEMICAL RESISTANCE OF VISTALON 6505 COMPOUND *#@

Chemical	Volume Change (%)	Tensile Strength Retained (%)	Elongation Retained (%)	Hardness Change (Pts.)	Surface Condition
A.S.T.M. No. 1 Oil	+115.3	36.1	42.0	-27	Unchanged
A.S.T.M. No. 3 Oil	+198.9	27.8	27.9	-31	Unchanged
A.S.T.M. Fuel B	+211.0	18.6	18.0	-31	Unchanged
Ethyl Alcohol	+1.25	82.1	88.5	-2	Unchanged
Hexane	+192.1	19.4	23.0	-28	Unchanged
Hydrochloric Acid (10%)	+0.6	98.9	95.1	+1	Unchanged
Methyl Ethyl Ketone	+2.8	82.5	86.9	-5	Unchanged
Sodium Chloride (25%)	-0.2	94.3	91.8	+2	Unchanged
Sodium Hydroxide (10%)	0	98.5	93.4	+1	Unchanged

* Exxon Elastomers/Chemical Resistance Handbook.

Vistalon 6505 is an ultra-fast curing EPDM that can be blended and covulcanized with many specialty and general purpose rubbers.

@ Six-month immersion at 75 F \pm 5°.

to ozone and ultraviolet radiation, is extremely impermeable to water, and retains flexibility throughout its service life with a high tolerance for extremes of temperature. It has good tensile and tear strength, good resistance to puncture, and desirable elongation qualities. One of its disadvantages is low resistance to hydrocarbons (petroleum solvents) and aromatic and halogenated solvents. Butyl rubber liners also have poor workability and poor seamability, which requires that special two-part temperature vulcanizing adhesives and cap strips be applied under dry conditions.^{1,2}

Hypalon^{1,2,4}

Hypalon is a widely used synthetic rubber that provides exceptional weather, ozone, and sunlight (UV) resistance. It will not crack or fail at extremes of temperature or from weathering. Hypalon is highly resistant to a wide range of chemicals, acids, and alkalis. It has moderate resistance to oils and growth of mold, mildew, fungus, or bacteria. Service life can generally be expected to exceed 20 years without a protective covering of soil. Usually supplied in the unvulcanized form it can be seamed by heat sealing or by solvent welding. Its disadvantages are relatively high cost and relatively low tensile strength.

EPDM

Ethylene propylene rubber is a high-strength, flexible compound traditionally designed especially for contact with potable water. It is highly impermeable, has excellent resistance to weather and ultraviolet exposure, resists abrasion and tear, and has a good tolerance for extremes of temperature. EPDM is also resistant to dilute concentrations (10 wt %) of acids, alkalis, silicates, phosphates, and brine. EPDM is not recommended for petroleum solvents (hydrocarbons) or for aromatic or halogenated solvents (Table 9). This compound can be sealed with a one-step EPDM adhesive and can be expected to last 15 to 20 years in normal use.^{1,2}

CPE

Chlorinated polyethylene is produced by a chemical reaction between chlorine and polyethylene and resembles a soft vinyl in texture. Since it is a completely saturated polymer (no double bonds), it is not susceptible to ozone attack. The compound also has excellent crack resistance at low temperatures and good tensile and elongation strength. Though CPE has excellent resistance to atmospheric deterioration, it has a rather limited range of tolerance for chemicals, oils, and acids. It can be compounded with other plastics and rubbers and still retain most of its desirable characteristics, making it a feasible base material for a broad spectrum of liners designed for specific applications. CPE has been successfully blended with polyethylene, PVC, acrylonitrile-butadiene-styrene resin, and several synthetic rubbers. It is widely used to improve stress crack resistance and softness of ethylene polymers and to improve cold crack resistance of flexible vinyls. CPE membranes are generally unvulcanized and thus can be seamed by solvent adhesives, by solvent welding, or by heat sealing.

Neoprene

Neoprene is a chlorine-containing synthetic rubber closely paralleling natural rubber in flexibility and strength. However, it is superior to natural rubber in resisting oils, weathering, ozone, and ultraviolet radiation. Neoprene is extremely resistant to puncture, abrasion, and mechanical damage. This compound is used primarily for the containment of wastewater and other liquid containing traces of hydrocarbons. It also gives satisfactory service with certain combinations of oils and acids for which other materials do not provide long-term performance. Neoprene membranes are vulcanized and consequently require curable adhesives in making seams. They are expensive compared with other flexible liners.

Polyethylene

This thermoplastic material is tough, highly flexible, and inert in solvents. It also has excellent low temperature qualities, but it has poor puncture resistance and weatherability if formulated without carbon black or ultraviolet absorbers. These deficiencies can be overcome with adequate protective soil covering. However, this lining material is difficult to place and seam in the field. Its initial cost is relatively low.

Polypropylene

Though prone to ultraviolet attack when formulated without carbon black, polypropylene has a desirable balance of other physical properties. It is tolerant to many chemicals and extremes of temperatures, particularly high temperatures. This compound has good tensile strength and low permeability to water. It is difficult to seam in the field. Polypropylene is not recommended for the containment of oxidizing solvents.^{1,2}

PVC

Polyvinylchloride is the most widely used liner material because of its relatively low initial cost and tolerance to a wide range of chemicals, oils, greases, and solvents. Though not as resistant to ozone, ultraviolet radiation, and weather deterioration as some of the other liner materials, it can provide long, satisfactory service in many situations if covered with soil. Exposed areas may be covered with materials of greater weatherability to improve service life-expectancy. PVC has a high strength-to-weight ratio and good resistance to puncture, abrasion, and microbiological activity. Exposure to heat causes undesirable deterioration in the presence of some chemicals. It also becomes stiff at low temperatures, making installation and maintenance more difficult in cold weather.

FABRIC-REINFORCED MEMBRANE LINERS

Flexible liners are also available in reinforced form. These are prepared by laminating fabric (or scrim) between layers of the basic material. The resulting advantages of the reinforced liner include a potential reduction in total thickness, a higher tear strength, more resistance to creep and ozone

deterioration, puncture resistance, dimensional stability, added resistance to seepage, and greater hydrostatic load capacity.⁵

Reinforcing fabrics are available in many materials and strengths.⁵ Among the more commonly used scrim fabrics are nylon, dacron, polypropylene, and glass fiber. Scrim selection would be determined by the chemical composition of the fluids to be contained, the slope of the installation site, and the stresses of equipment or other mechanical forces to which the liner will be exposed.

The principal disadvantages of reinforced liners are low elongation to break, less ability to conform to ground irregularities, less flexibility, and greater cost than unreinforced liners by 30% to 60%.⁵

SELECTING FLEXIBLE MEMBRANE LINERS FOR IMPOUNDMENT SITES^{1,2}

In selecting a flexible membrane liner for a specific impoundment site for the containment of industrial wastes, the following criteria should be considered:

- The liner material should satisfactorily resist attack from all chemicals (solvents, oils, greases, etc.), ozone, ultraviolet radiation, soil bacteria, mold, and fungus to which it will be exposed, as evidenced by sufficient laboratory testing.
- It should have ample weather resistance to withstand the stresses of freezing, thawing, and periodic shifts of the earth.
- The liner should have adequate tensile strength and flexibility, and it should be able to elongate sufficiently to withstand the stresses of installation or use of machinery or equipment without failure.
- It should resist laceration, abrasion, and puncture from any matter that may be found in the fluids that it will contain.
- All the membrane material in a given installation should be of uniform thickness and of the same material furnished by the same manufacturer to ensure good seaming.
- The liner should be free of gels, streaks, particles of foreign matter, and undispersed raw material. There should be no physical defects such as cracks, crazes, tears, or blisters. Pinholes should not exceed one per 8.4 m² (10 yd²) of liner material.
- It should be of sufficient thickness to guarantee long-term service in the specific application.
- The liner should be capable of being repaired easily at any time during its life, and it should be the most economical material that can adequately fill the specific need.

CONTRACTOR CONSIDERATIONS

The choice of both the membrane liner and the installing contractor is very important in constructing impoundment sites for the containment of industrial waste, particularly since these structures will be expected to perform without significant leakage for several decades. Such a choice cannot be made by evaluation of liner material alone. Rather, the ultimate success of the

impoundment site will depend to a large extent on the experience of the liner vendor and the installing contractor.

Many parameters should be evaluated to obtain optimum performance for cost in a specific installation. Such parameters should include a complete description of the factory-produced seam and its properties, as well as the field seam used by the contractor and the effect on the factory and field joints of long-term immersion in the fluid to be contained. Ultimately, however, the success of the impoundment site depends on the integrity and experience of the membrane liner manufacturer and the installing contractor, their guarantees, and their financial abilities to support the guarantees.⁶

INSTALLATION OF FLEXIBLE MEMBRANE LINERS

Installation of the liner is as important as selection of the material itself.⁷ Improper installation of even the best material will defeat the purpose of the lining. The following discussion provides guidelines for the installation of flexible membrane liners.

Planning

The planning and laying out of the lagoon, pit, pond, etc. should be done very carefully, for this is the first step that will determine the ultimate success of the installation.

Contracting

Installation of the liner should be done by a qualified, experienced contractor. Even though a turnkey job may not be desired, a contractor experienced in designing, building, piping, lining, and doing the complete job can be a definite asset.

Surfacing

The surface over which the liner is to be placed should be clear of all debris, vegetation, and sharp objects, and it must properly support the liner. If possible, the surface should be covered with a few inches of sand, clay, or other fine-textured soil. All surfaces should be well compacted.³

Sloping

Side slopes of the installation berms should be at least 3:1, preferably flatter unless specifically designed.^{1,2,3}

Trenching

An excavated perimeter trench on top of the berm, 15.24 cm (6 in.) minimum in width and 30.48 cm (1 ft) minimum in depth, should be used for anchoring the edges of the liner. This trench should be at least 60.96 cm (2 ft) from the top inside slope of the dike. On side slopes over 12.19 m (40 ft) in length, intermediate trenches should be used to anchor the liner.^{1,2,3}

Joining

Since factory joints or seams are usually better than field seams, liner sections should be factory seamed to form sheets at least 15.24 m (50 ft) wide. Before making the field seams, all the wrinkles should be removed from the surfaces of the liner to be sealed. These surfaces should also be clean and dry.^{1,2,3}

Field seams should be overlapped at least 5.08 cm (2 in.), but not more than 15.24 cm (6 in.), to avoid unnecessary waste of material. Seams can be made by heat-welding, cementing, solvent welding, adhesive tape, zipper, or sewn-in-place techniques, depending on the polymer and the compound formulation of the liner. The heat-weld method is felt to give superior seams in that no foreign material is added to the liner. Both factory and field joints must be strictly supervised, for an ineffective seam will eventually cause leakage.^{1,2,3}

Covering

To provide longer life and protection against mechanical damage from falling objects, vandalism, and sunlight, it is strongly recommended that flexible membrane liners be covered, if possible, with a layer of sand or soil.³

ECONOMICS

The 1973 cost of flexible membrane lining material varied from \$0.10 to \$0.60/0.09 m² (1 ft²), and the corresponding installation cost varied from \$0.01 to \$0.10/0.09 m² (1 ft²). Figure 1 shows the 1973 costs for construction of an evaporating pond, including earthwork, related piping, lining material, installation, and placement of an earth cover. More information concerning cost of individual flexible membrane liners may be found in Table 10. For additional cost information see Rossoff and Rossi.⁸

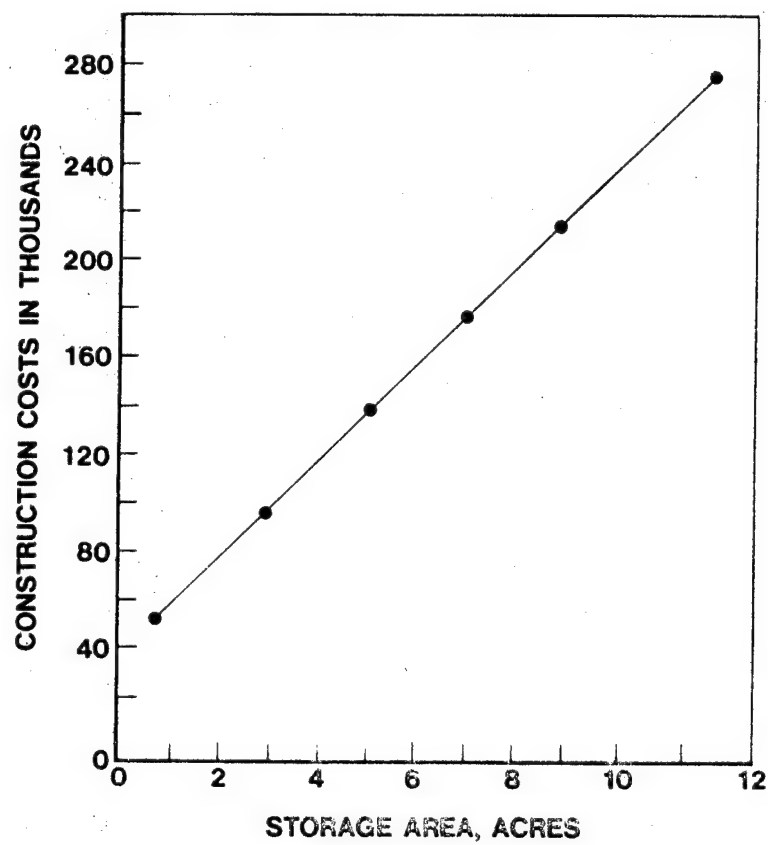


Figure 1. Construction costs of evaporation ponds¹ in 1973.

CONSTRUCTION COSTS IN THOUSANDS

STORAGE AREA, ACRES

TABLE 10. COSTS FOR INSTALLED FLEXIBLE MEMBRANE LINERS IN 1973.

Type of Liner	\$/ft ²
Exposable Liners:*	
Butyl:	
30 mils #	0.30
47 mils	0.36
EPDM:	
30 mils	0.29
47 mils	0.35
CPE:	
20 mils	0.26
30 mils	0.34
Hypalon:	
20 mils	0.26
30 mils	0.34
Neoprene:	
47 mils	0.49
Unexposable Liners: *	
Polyethylene:	
20 mils	0.15
Polypropylene:	
20 mils	0.17
PVC:	
20 mils	0.18
30 mils	0.22

*Nylon-scrim-reinforced liners cost about an additional \$0.10/ft².

#1 mil=0.001 in.

SECTION 5

ASPHALT MATERIALS AS LINERS FOR IMPOUNDMENT SITES

The possibilities of using admixed materials such as asphalt concrete, bituminous seal, soil asphalt, and sprayed asphalt membranes as linings in land impoundment sites have long been recognized. The primary advantages of asphalt materials are their universal availability, low cost, extreme versatility in available physical forms, and the fact that asphaltic materials are some of the most logical engineering materials available for large-scale waterproofing construction. The use of pure asphalt in membrane form constitutes a most effective construction form from the standpoint of seepage control and cost effectiveness. But if it is fully exposed, this form has serious disadvantages in subgrade foundation requirements, weathering and aging because of exposure to solar radiation and heat, erosion from turbulent water, and damage from mechanical equipment.⁹ To a large degree, correction of these disadvantages was proven possible in prime-membrane type asphaltic linings in which deep subgrade treatments and filled asphalt membranes were used, but the cost of such construction remained unduly high. To retain the advantages of a membrane lining while eliminating or minimizing the disadvantages, new types of asphaltic materials were developed.

ASPHALT CONCRETE

Asphalt concrete is a carefully controlled mixture of asphalt cement and graded aggregate that is placed and compacted at elevated temperatures. Asphalt concrete is especially well adapted to the construction of linings for all types of hydraulic structures. It may be used for the entire lining structure, or it may be a principal part of a more complex lining. Depending on mix design and placement, it may serve as an impermeable layer or as a porous layer. Properly mixed and placed, asphalt concrete forms a stable, durable, and erosion-resistant lining.

Asphalt cements of 40 to 50 or 60 to 70 penetration grades are preferable for hydraulic concrete linings.^{9,10} The lower penetration grades produce harder asphalt concrete linings that are more resistant to the destructive action of water, the growth of vegetation, and extremes of weather. They are more stable on side slopes than linings made with sulfur asphalt cements, but they retain sufficient flexibility to conform to slight deformation of the subgrade.

Mix design of asphalt concrete for hydraulic linings follows general principles such as those described in publications of the Asphalt Institute.^{11,12}

Table 11 lists some typical mix compositions. The maximum stone size will generally be from 1.27 to 2.54 cm (1/2 to 1 in.) in size, and the amount of mineral filler passing a No. 200 sieve will usually be from 8% to 15%. The mix should have 6% to 9% asphalt content by weight of the total mix. The aggregate gradation and asphalt content should be such that the mix will be stable, yet easily compacted to less than 4% air voids.

SOIL ASPHALT

Soil asphalt embraces a wide variety of soils, usually those of low plasticity mixed with a liquid asphalt. Generally, soil asphalt mixtures are avoided for lining purposes.^{9,10} There are always exceptions, but soil asphalt mixes containing cutback asphalts are usually not suitable for linings.^{9,10} (Cutback asphalts are liquid solutions of asphalt in a volatile solvent. Upon evaporation of the solvent, cutback asphalts assume a heavy consistency typical of the base asphalt.¹³) Those soil asphalts containing emulsified asphalts require a waterproofing seal, membrane, or asphalt concrete to be placed on top of them. (Asphalt emulsions are dispersions of

TABLE 11. SUGGESTED MIX COMPOSITIONS FOR
DENSE-GRADED ASPHALT CONCRETE LININGS¹²

Sieve Size	% Passing	
	For Minimum thickness of 3.31 cm (1 1/2 in.)	For minimum thickness of 2.54 cm (1 in.)
1.9 cm (3/4 in.)	100	n/a
1.3 cm (1/2 in.)	95-100	n/a
0.95 cm (3/8 in.)	n/a	100
No. 4	60-80	90-97
No. 8	45-60	70-85
No. 10	n/a	n/a
No. 30	28-39	42-52
No. 40	n/a	n/a
No. 100	16-25	20-28
No. 200	8-15	10-16
Asphalt Cement of Total Mix (wt %)	6.5-8.5	7.5-9.5

microscopic asphalt particles in a continuous aqueous phase containing small amounts of chemicals or clay as emulsifiers. They can be classified as anionic, cationic, or nonionic, depending on the electrical charge on the asphalt particles. Asphalt emulsions are normally liquid, reverting to the solid or semisolid state of the base asphalt after application by means of evaporation or breaking out of the water.¹³⁾

SPRAYED ASPHALT MEMBRANES

An asphalt membrane lining (hot-sprayed type) consists of a continuous layer of asphalt, usually without filler or reinforcement of any kind. It is generally covered or buried to protect it from mechanical damage and to prevent weathering (oxidation) of the surface. Its cover may be another layer of a multilayer lining structure, but generally it is native soil, gravel, asphalt macadam, or other substances specifically placed for this purpose. Asphalt membranes are placed to thicknesses of 0.48 to 0.79 cm (3/16 to 5/16 in.) and constitute continuous waterproof layers extending throughout the length and breadth of the structure being lined. Asphalt of special characteristics is used to make these membranes into tough, pliable sheets that readily conform to changes or irregularities in the subgrade. Buried under a protective coating, an asphalt membrane will retain its tough, flexible qualities indefinitely. It is one of the least expensive types of current liners.

Asphalts used to make membranes must have very low temperature susceptibility and a high degree of toughness and durability. Furthermore, asphalt for membrane linings must have a high softening point to prevent sagging or flow down a slope if the cover material should be accidentally removed and the membrane exposed to the sun. The material must also be sufficiently plastic at operating temperatures to minimize the danger of rupture from earth movement. Also, it must not exhibit excessive cold flow tendencies in order to effectively resist the hydraulic head to which it is subjected.

Considerable laboratory research and field trials have gone into the selection of suitable asphalts. Those that meet the requirements are usually asphalts produced from selected feedstocks by the use of air-blowing techniques. (Some manufacturers employ chemical modifiers, which are most often termed catalysts, in the blowing process.) Specifications⁹ that have been adopted as tentative by the Asphalt Institute appear in Table 12.

BITUMINOUS SEALS^{9,10}

Bituminous seals are generally used to seal the surface pores of an asphalt mixture serving as a lining or to provide additional assurance for waterproofing. They are also considered in some cases where there may be some reaction between the aggregate in the mix and the liquid to be stored. There are basically two types of bituminous seals. One is simply an asphalt cement (sometimes emulsified asphalt is used instead) sprayed over the lining surface at a rate of about 1.1 liter/m² (1 qt/yd²). This method provides a film approximately 0.18 cm (1/32 in.) thick. The second type of seal consists of an asphalt mastic that may contain 25% to 50% asphalt cement. The remainder

TABLE 12. TENTATIVE SPECIFICATIONS FOR ASPHALT FOR HYDRAULIC MEMBRANE
CONSTRUCTION* AS OF DECEMBER 1965 #

Characteristics	AASHO Test Method	ASTM Test Method	Grade
Softening Point (Ring and Ball), F	T-53	D-36	175-200
Penetration of Original Sample			
At 32 F, 200 g, 60 sec	T-49	D-5	30+
At 77 F, 100 g, 5 sec			50-60
At 115 F, 50 g, 5 sec			120-
Ductility at 77 F, cm	T-51	D-113	3.5+
Flash Point (Cleveland Open Cup), F	T-48	D-92	425+
Solubility in Carbon Tetrachloride, % @	T44-64I	D-2042	97.0+
Loss on Heating, 325 F, 5 hrs, %	T-47	D-6	1.0-
Penetration after Loss on Heating, % of Original	T-49	D-5	60+
General Requirements	The asphalt shall be prepared by the re- fining of petroleum. It shall be uniform in character and shall not foam when heated to 400 F.		

*Adapted from Reference 9.

#See the Asphalt Institute specifications for asphalt cements and liquid
asphalts (SS-2), Reference 12, for latest revisions.

@Alternatively, trichloroethylene (not trichloroethane) may be used as the
solvent for determining solubility. In the case of dispute, however,
carbon tetrachloride will be used as the referee solvent.

is a mineral filler such as limestone dust or an inexpensive reinforcing fiber such as asbestos. This mixture is generally squeegeed on at an application rate of about 2.7 to 5.4 kg/m² (5 to 10 lb/yd²).

CHEMICAL RESISTANCE AND IMPERMEABILITY OF ASPHALT LININGS

Asphalt linings have generally been found to be quite stable in the presence of most industrial waste solutions. The exceptions occur when the wastes contain fairly high concentrations (more than 5 wt %) of petroleum (hydrocarbon) solvents, oils and fats, and some aromatic solvents (toluene, etc.). However, asphalt linings are resistant to methyl, ethyl alcohols, and glycols. The common mineral acids, other than nitric, do not visibly attack asphalt at moderate concentrations and temperatures. Asphalt is resistant to mineral salts and to alkalis to at least 30% concentration. Asphalt shows good resistance to corrosive gases such as hydrogen sulfide and sulfur dioxide, but it may show variable-to-poor performance when exposed to hydrogen halide vapors. Table 13 provides information regarding the chemical resistance of unmodified asphalt.

Asphalt concrete linings should have less than 4% voids if compacted properly. If this is done, it is widely accepted that the coefficient of permeability (K) will be less than 1×10^{-7} cm/sec. Also, the permeability of a dried asphalt coating 0.32 cm (1/8 in.) thick (measured by the wet cup method) is about 0.01 grains of water vapor/hr. ft² per inch of mercury pressure differential across the film, or 0.01 perms.^{9,10} It is also accepted that this is considered to be waterproof.¹⁰ Seepage calculations for a given head, lining thickness, and lining area may indicate otherwise, but the experience of the Asphalt Institute and test conducted in their laboratory¹⁰ show that the well designed mix (described earlier in Table 12) will be essentially impermeable to water (K=0). Any voids in an asphalt lining can be attributed to trapped air bubbles, and as long as they are not interconnected, the compacted lining will be watertight. In a practical sense, the design should not allow for construction inequities that may occur during the placing and compacting of the lining. Construction or paving joints are subject to be the weakest part of the lining, and steps should be taken to minimize possible leakage at these joints. The impermeable portion of the liner should therefore consist of at least two paving courses, with offset paving joints. To assure good control in the spreading and compacting of these layers, a leveling course of minimum thickness is generally recommended to provide a satisfactory surface. Depending on the conditions, an additional course with offset paving joints may be placed as the final surface layer. This amounts to two or three paving courses placed on a leveling course. The minimum course thickness will be governed by the maximum size of stone particles in the asphalt mix. The paving course should be at least three times the maximum particle size (1.27 cm, or 1/2 in.) aggregate. Finally, a well designed and placed asphalt lining does not require a surface seal to insure a watertight liner. However, liner consultants frequently require this, possibly as a final assurance.

TABLE 13. CHEMICALS RESISTED BY UNMODIFIED ASPHALT¹³ (to 150 F)*

Alum	Hydrochloric acid, 10%	Potassium ferrocyanide
Aluminum chloride	Hydrochloric acid, conc.*	Potassium hydroxide, 30%*
Aluminum nitrate	Hydrocyanic acid	Potassium nitrate
Aluminum potassium sulfate	Hydrogen sulfide gas, dry	Potassium sulfate
Aluminum sulfate	Hydrogen sulfide gas, wet	Salicylic acid
Ammonium chloride	Iron chlorides (ferric and ferrous)	Silver nitrate
Ammonium hydroxide*	Iron nitrates (ferric and ferrous)	Sodium acetate
Ammonium nitrate	Iron sulfates (ferric and ferrous)	Sodium bicarbonate
Ammonium sulfate	Lactic acid	Sodium carbonate
Barium chloride	Lead acetate	Sodium chloride
Barium hydroxide	Lead nitrate	Sodium cyanide
Barium nitrate	Magnesium chloride	Sodium hydroxide, 30%*
Benzoic acid	Magnesium hydroxide	Sodium nitrate
Boric acid	Magnesium nitrate	Sodium potassium tartrate
Cadmium chloride	Magnesium sulfate	Sodium sulfate
Cadmium nitrate	Mercuric acetate	Sodium sulfite
Calcium bisulfite	Methyl alcohol	Sodium thiosulfate
Calcium chloride	Nickel chloride	Sulfur dioxide gas, dry
Calcium hydroxide*	Nickel nitrate	Sulfur dioxide gas, wet
Calcium nitrate	Nickel sulfate	Sulfur trioxide gas, dry
Chlorine gas, dry	Oxalic acid	Sulfur trioxide gas, wet
Chlorine gas, wet*	Phosphoric acid	Sulfurous acid
Citric acid	Phosphorous acid	Tannic acid
Copper chloride	Phosphorous trichloride	Urea
Copper nitrate	Phthalic acid	Zinc chloride
Copper sulfate	Potassium bicarbonate	Zinc nitrate
Ethyl alcohol	Potassium carbonate	Zinc sulfate
Ethylene glycol	Potassium chloride	
Glycerine	Potassium cyanide	
Gold cyanide (auric cyanide)	Potassium ferricyanide	

*Indicates to 80 F, only.

MATERIAL AND INSTALLATION COSTS, EQUIPMENT, AND METHODS

Material costs of asphalt linings vary and depend greatly on the locale. Except for the membrane asphalt, the required materials are normal paving ingredients and should cost no more when used for lining purposes. Some relative costs of asphalt lining materials are listed in Table 14. However, installation costs are generally higher. For example, a ton of asphalt concrete lining in place may cost two to four times as much as it would on a roadway.¹⁰ But other factors are to be considered, such as the sloped surfaces, offset paving joints, and multiple paving courses. Regular road paving equipment is used whenever possible for constructing an asphalt lining. If the installation is large enough, and if it is economically justified, special equipment can be designed and constructed for the job.

MAINTENANCE

Properly constructed, an asphalt lining should require little if any maintenance. Sometimes an algae or clay deposit along the waterline may tend to pull the asphalt seal from the surface through repeated drying and wetting, or there may be some evidence of scour, as has been observed in asphalt-lined canals. Timely treatment of these areas with an asphalt seal, or even a slurry seal, can minimize wear. These are exceptions and are evident in only a few potable water installations. Sometimes cracks occur, especially at paving joints. But with multilayer construction, these cracks are only one paving course deep, unless they result from differential settlement of the structure to an excessive degree. Ordinary crack-filling methods have been used with success. A properly designed and constructed lining installation should pose few maintenance problems.

TABLE 14. COSTS OF VARIOUS ASPHALT LINER MATERIALS^{14,15}

Material	Installed Cost* (\$/ft ²)
Paving asphalt with sealer coat (5.1 cm, 2 in.)	0.13-0.19
Paving asphalt with sealer coat (10.2 cm, 4 in.)	0.26-0.36
Hot sprayed asphalt (4.5 liters/m ² , 1 gal/yd ²)	0.17-0.22 [#]
Asphalt emulsion sprayed on polypropylene fabric (100 mils)	0.14-0.21
Asphalt membrane	0.14
Asphalt concrete	0.20

*Costs do not include construction of subgrade or cost of an earth cover. These can range from \$0.10 to \$0.50/yd² per foot of depth.

[#]Includes earth cover.

LIFETIME OF ASPHALT LININGS

Most of the documented information concerning the life expectancy of asphalt linings exists for the buried membrane linings. However, asphalt concrete linings have served satisfactorily for the life of a structure. Potable water reservoir linings placed in California more than 20 years ago continue to serve with no projected failure or termination date established.¹⁰ The Montgomery Dam in Colorado, probably with as severe a performance requirement as any in the United States, performs satisfactorily after nearly 20 years of continuous service.¹⁰

SECTION 6

SOIL SEALANT LINERS FOR IMPOUNDMENT SITES

Seepage of industrial wastes from various unlined types of impoundment sites can render adjacent land unsuitable for growth of any type of vegetation and hazardous for occupation by any kind of living creature. The problem is compounded by the fact that the seepage may ultimately find its way into streams and rivers where it can be hazardous to aquatic life and adjacent land areas for many miles.

Coyle¹⁶ has summarized the principal causes of seepage from unlined impoundment sites as:

- Permeable soils or strata of sand or gravel in the reservoir area.
- Shallow soils underlaid by fractured bedrock, solution cavities, bedding plains, etc.
- Flocculated residual soils over cavernous and fractured limestone and calcareous shale.
- A gypsum content of the soil high enough to create significant voids as the gypsum is dissolved.

Under certain conditions, soil permeability may be reduced by the application of various chemicals.^{17,18} Chemical sealing agents react with soil constituents to form a more impermeable membrane. Since no single chemical has been reported to seal all soils effectively, tests must be performed on each type of soil to determine what seepage rates will obtain. Chemical sealing agents must be:

- Nontoxic to humans, animals, and crops.
- Able to reduce seepage to at least 0.1 to 0.3 ft/ft² per day.
- Capable of nonrestrictive application under a broad range of soil compositions in static or dynamic flow conditions.
- Able to resist damage by animals, equipment, erosion, and hydraulic pressures (that is, 20 psi).
- Durable and resistant to deterioration by climatic conditions such as freezing and thawing, sunlight, wetting and drying, soil microorganisms, re-emulsification or chemical change, and reverse hydraulic flow.
- Capable of resealing.
- Efficient in the use of material (low cost).

Unfortunately, the life of most soil sealants is affected by freezing and thawing, wetting and drying, reaction with constituents in the pond wastes, and leaching of the sealing agent by waste liquid.

Polymeric soil sealants are a fairly recent development.¹⁹⁻²² Most of these materials consist of a blend of a high-molecular-weight linear polymer

and a crosslinked, swellable polymer of approximately the same molecular weight. The linear polymer's many sorptive sites allow it to sorb to the soil and form a flexible network. The crosslinked polymer is extrudable and can conform to permeability channels in the soil without loss of integrity. In use, the polymer system helps to form a stabilized soil surface of extremely low permeability.

Formulation of the polymeric soil sealant system depends on its use, and in most instances, it is considered to be proprietary by the marketing company. When used in unfilled impoundments, the polymer is mixed in a low-pH water/acid solution and then sprayed on the earthen surface as a low-viscosity slurry. The low-pH condition allows the polymer to penetrate the surface. Upon subsequent exposure to water, the water-swellable portion swells and becomes locked in place. The linear polymer, being sorptive in this state, attaches to the soil to complete formation of the stable, impermeable surface.

Another formulation that has been successfully used is a bentonite/polymer system in which bentonite replaces the crosslinked polymer portion. Bentonite is not as efficient as the crosslinked polymer, but it is considerably cheaper on a per-pound basis. When it is important to structurally improve the impoundment, the use of bentonite with a linear polymer or with a blend of polymers is advantageous.

APPLICATION OF POLYMERIC SOIL SEALANTS

There are three basic methods of application of polymeric sealants: (1) dry blending, (2) spraying in slurry form, and (3) dusting as a free-flowing powder.

Bentonite/polymer mixtures may be applied either by dry blending or spraying in slurry form. When this sealant is dry blended into the soil, standard highway compaction procedures and blending equipment may be used. Compaction by rubber-wheeled compactors is desirable. If the sealant is applied by spraying, special equipment and techniques are required. The polymer sealant may be sprayed as a slurry across the area to be sealed. The slurry, which is formed by carefully blending a dry powder into fresh water, is reported to be somewhat viscous and slightly acidic. But it has been successfully applied by water-hauling trucks equipped with centrifugal pumps, hoses, and adjustable fire nozzles.

Application of the sealant as a dry powder can be accomplished by dusting across the surface using any equipment suitable for dispersing a powder. The size and shape of the impoundment site normally dictates the type of equipment required.

EFFICIENCY OF SOIL SEALANT SYSTEMS

The first of several factors that affect the efficiency of polymeric sealants is the method of application. Dry-blending provides the most effective method. Its use is also desirable where structural strengthening of

the impoundment is required. The order of effectiveness of the other methods is spraying and dusting.

The amount of material used in an application also appears to influence the overall efficiency of the soil sealant. But to date, no actual field data are available for comparisons.

Other factors influencing efficiency are degrees of soil compaction and composition of the impoundment water. The data in Tables 15-17 list some representative soil sealants and the effects of factors such as soil compaction and water composition.

TABLE 15. REPRESENTATIVE SOIL SEALANTS²²

Sealant	Application	Remarks
Cationic Asphalt Emulsion	Farm Ponds	Requires approximately 19,000 l / 4,047 m ² (5,000 gal/acre) dispersed in water.
Oil Soluble Polymers in Diesel Fuel	Fresh Water	Injected beneath surface of water where seepage was occurring.
Sodium Tetraphosphate	Sulfite Liquor Storage	Dispersant distributed in 15.2-cm (6-in.) layer of soil at 2.3 kg/9 m ² (5 lb/100 ft ²). Careful compaction rendered soil impervious.
Sodium Carbonate	Canals	Wet-dry cycles disrupt water barrier. Used 183 g (0.4 lb) of reagent/0.84 m ² (yd ²) of soil.
Lignin Derivatives Gelled Alum	Desalination Byproduct Brine	1% lignin cost \$3,400/4,047 m ² (acre).
Carboxymethyl Cellulose with Alum	Desalination Byproduct Brine	0.2% CMC cost \$2,250/4,047 m ² (acre).
Petroleum Emulsions	Desalination Byproduct Brine	4% additive cost \$4,400/4,047 m ² (acre).
Attapulgate Clay	Desalination Byproduct Brine	2% Zeogel cost \$1,000/4,047 m ² (acre).
Liquid Elastomeric Polymer	Fresh Water	Patent discloses several compositions, including polyurethane elastomers. ²³

TABLE 16. INFLUENCE OF COMPACTION ON RATE OF SEEPAGE
THROUGH SOIL TREATED WITH SEALANT*

Density of Soil kg/0.03 m ³ (lb/ft ³)	Seepage Rate--cm/day (in./day)			
	Original	1 day	7 days	
42.2 (93)#	124.5 (49)	-- --	-- --	
42.2 (93)@	-- --	50 (19.7)	108.7 (42.8)	
47.7 (105)#	27.9 (11.0)	-- --	-- --	
47.4 (105)@	-- --	4.8 (1.9)	3.3 (1.3)	
50.4 (111)#	12.2 (4.8)	-- --	-- --	
50.4 (111)@	-- --	2.3 (0.9)	1.02 (0.4)	

*Sealant is a product of Dowell, Division of Dow Chemical Company, Tulsa, Oklahoma, 74102. Soil and water are from Altus, Oklahoma, irrigation district.

#No sealant applied.

@Sealant, J225, applied at rate of 363 kg/4,047 m² (800 lb/acre).

TABLE 17. INFLUENCE OF WATER COMPOSITION ON RATE OF SEEPAGE
THROUGH SOIL TREATED WITH SEALANT*##@

Sealant	Seepage Rate--cm/day (in./day)			
	Original	1 day	7 days	
None	24.6 (9.7)	-- --	-- --	
363 kg/4,047 m ² J225 (800 lb/acre)	-- --	10.4 (4.1)	12.7 (5.0)	
181.5 kg/4,047 m ² J225 (400 lb/acre) + 118 kg/4,047 m ² soda ash (260 lb/acre)	-- --	1.2 (0.48)	1.1 (0.42)	
None	45.7 (18.0)	-- --	-- --	
363 kg/4,047 m ² J225 (800 lb/acre)	-- --	19.8 (7.8)	14.7 (5.8)	
181.5 kg/4,047 m ² J225 (400 lb/acre) + 295 kg/4,047 m ² soda ash (650 lb/acre)	-- --	2.3 (0.9)	1.5 (0.6)	

*Southwest Colorado. Sealant is a product of Dowell, Division of Dow Chemical Company, Tulsa, Oklahoma.

#Water contained excess amount of divalent cations; sodium carbonate was added to lower calcium content.

@In all cases, density of soil was 46.8 kg/0.03 m³ (103 lb/ft³).

LIMITATIONS OF SOIL SEALANT SYSTEMS

Polymeric sealants do not in themselves provide structural strength. A wastewater impoundment site that has not been compacted will still be weak following a treatment with sealants. Impoundments must be compacted. Dry reservoirs can be compacted using mechanical methods, and those that are filled can be compacted hydraulically by exposure for sufficient time. When seepage rates are stabilized, maximum hydraulic compaction has been obtained.

Exposure to salts and acids that cause the polymers to shrink will affect the efficiency of the seal. Exposure to the same acidic conditions that allow the slurry form to be used will decrease the effectiveness of the seal once in place and exposed to waters of higher pH.

Similarly, exposure to salts, especially multivalent cations, cause a decrease in polymer volume. Exposure to the same salts that retard hydrolysis of the polymer and allow the powder form to be used decreases the efficiency of the seal established against fresh water.

In spite of these limitations, polymer sealant systems deserve further study for possible use as sealants in industrial waste impoundments.

Rubber latex has been used in sealant studies to control acid mine drainage.²⁴ The seal penetrated the top 25.4 cm (10 in.) of soil, which was unsatisfactory for the testing purposes. But additional investigations may prove the suitability of latex as a sealant for waste impoundment sites.

SOIL CEMENT

Soil cement is prepared by compacting a mixture of Portland cement, water, and a wide variety of soils. As the Portland cement hydrates, the mixture becomes a hard, low-strength Portland cement concrete. Soil cement is sometimes used to surface pavements with low-volume traffic, and it is extensively used for the lower layers of pavements, where it is generally referred to as cement-treated base. Soil cement is also widely used in water control construction, more specifically to protect the slopes at earth dams and other embankments. See Appendix D for information regarding contract awards for soil cement water control projects.

Strong soil cement linings can be constructed using many types of soils, but the permeability of the resulting liners varies with the nature of the soil: The more granular it is, the higher the permeability. By using fine-grained soils, soil cements with permeability coefficients of about 10^{-6} cm/sec can be obtained. In actual practice, surface sealants are often applied to soil cement linings to obtain a more waterproof structure. Aging and weathering characteristics of soil cement linings are fairly good, especially those associated with the wet-dry and freeze-thaw cycles. Some degradation of soil cement linings can be expected in an acidic environment, however.

SECTION 7

NATURAL SOIL SYSTEMS AS LINERS FOR IMPOUNDMENT SITES

Seepage of liquids commonly occurs through natural soils that contain little or no clay or silt. Therefore, the addition of selected clays offers a feasible method for limiting such losses.

SOIL/BENTONITE

High-swell clay minerals have been widely used to control excessive seepage in natural soils by decreasing their permeability. Bentonite, one of the most widely used clays, is a heterogeneous substance composed of montmorillonite and small amounts of feldspar, gypsum, calcium carbonate, quartz, and traces of other minerals. Bentonite has colloidal properties because of its very small particle size and the negative charge on the particles. About 70% to 90% of the particles are smaller than 0.6 micron.²⁵ Bentonite has the capacity of absorbing approximately five times its weight in water and occupies a volume of 12 to 15 times its dry bulk volume at maximum saturation.²⁶ It is this swollen mass that fills the voids in soils that normally would permit water seepage. These high-swell bentonites are found in Wyoming, South Dakota, Montana, Utah, and California.

The level of ionic salts found in certain industrial wastes is often sufficient to reduce the swelling of bentonite and therefore impair its usefulness as a sealant. Since the water that initially contacts the bentonite is most critical to its effectiveness, swelling of the bentonite can often be effected by prehydrating the bentonite in fresh water. This forms an effective seal in the presence of contaminated wastewater. But in the presence of high quantities of dissolved salts, the prehydrated clay eventually deteriorates. The use of a specially formulated form of bentonite (Saline Seal) reportedly assures that after prehydration, the bentonite will remain swollen for a long time and will not deteriorate as rapidly when exposed to a high level of ionic contaminants.

Saline Seal bentonite can be distributed over a prepared lagoon surface at a rate of about 1.82 kg/0.09 m² (2.0 lb/ft²) and mixed thoroughly into the top 5.1 to 15.2 cm (2 to 6 in.) of soil. The area is then covered with a minimum of 1 in. of fresh water to effect prehydration. After 2 to 4 days, industrial waste can be put into the lagoon.

Saline Seal can also be placed on unstable or wet soil surfaces as a slurry. Slurries are made by mixing approximately 0.23 kg (1/2 lb) of

Saline Seal per 3.8 liters (gal) of water. When distributed over the soil surface, the slurry will effectively seal the soil surface.

Table 18 compares the relative performance of a bentonite and Saline Seal, both of which were prehydrated with fresh water. The soil tests were performed on sandy soil, with 3.6 kg (4.0 lb) of each applied per 0.09 m² (ft²) and thoroughly mixed into the top 5.1 cm (2 in.) of soil. As the data indicate, the prehydrated bentonite seal showed signs of deterioration on the second day and failed completely on the seventh day, whereas the Saline Seal maintained and even improved the seal. The contaminated water used in the test contained 3.1% sodium chloride and 3.6% sodium sulfate.

TABLE 18. COMPARATIVE PERFORMANCE OF BENTONITE AND
SALINE SEAL BENTONITE IN A SOIL TEST²⁷

Day	Prehydrated Bentonite		Prehydrated Saline Seal	
	Permeability* (cm/sec)	Leakage Rate# cm (in.)	Permeability* (cm/sec)	Leakage Rate# cm (in.)
1	1.0 x 10 ⁻⁶	0.318 (0.125)	1.0 x 10 ⁻⁶	0.318 (0.125)
2	2.0 x 10 ⁻⁶	0.635 (0.250)	1.0 x 10 ⁻⁶	0.318 (0.125)
3	5.0 x 10 ⁻⁶	1.905 (0.750)	0.8 x 10 ⁻⁶	0.254 (0.100)
4	1.0 x 10 ⁻⁵	3.18 (1.25)	0.9 x 10 ⁻⁶	0.284 (0.112)
5	6.0 x 10 ⁻⁵	19.1 (7.5)	0.7 x 10 ⁻⁶	0.221 (0.087)
7 [@]	1.0 x 10 ⁻⁴	31.8 (12.5)	0.7 x 10 ⁻⁶	0.221 (0.087)

*1.0 x 10⁻⁶ cm/sec represents an effective seal (equivalent to 1 ft of compacted native clay).

#Loss of water at a 1.22-m (4-ft) head.

[@]Seal failed.

Low-swell clays such as hydrated mica and kaolin have had limited use as sealants. However, some research has been conducted on their sealing characteristics,²⁸ and perhaps additional investigations are needed. The low-swell clays are affected less by increased concentrations of magnesium or calcium in water, and the damage from drying may be less severe. Low-swell clays are generally found in Nevada and other western states.

The cost of bentonite-type clays varies from about \$10/ton to more than \$25/ton (FOB the clay-processing plant), with \$20/ton a typical cost.²⁸ The price variation is a function of the quality of the clay, the degree of carried out processing, and the quantity purchased. In addition to the basic cost, shipping is expensive unless the site is located near the clay-processing plant. Typical shipping costs range from \$20 to \$30/ton, depending on the mode of transportation and the distance traveled. Note, however, that if clay

suitable for an impoundment site lining is available on the site itself, the cost could be as low as \$1.00/0.8 m² (yd²) if the clay can be bulldozed into position.²⁹

COMPACTED SOILS

The characteristics of a soil suitable for compaction include low permeability, high stability, and good resistance to erosion. The moisture level in a soil affects the degree of compaction and consequently the permeability. An optimum moisture level exists for maximum compaction, after which increased permeability occurs. Also, the optimum moisture level for maximum compaction depends upon the type of soil. Therefore compaction tests should be performed on each soil to determine optimum conditions. Generally, when the moisture content of a soil is optimum, a compaction greater than 95% of maximum density can be obtained by making approximately six passes with a tamping roller followed by four passes with a rubber-tired roller.²⁹

Because soil permeability is inversely proportional to the thickness of the compacted layer, the soil should be compacted in 15.2-cm (6-in.) layers up to a depth of 3 ft. But even under the most optimum conditions of compaction, soil permeabilities may change over a period of time.

The waste contained in a compacted, earth-lined pond may have both detrimental and beneficial effects on the permeability of the soil. Acidic wastes can react with the soil and destroy its expansion capabilities. Alkaline wastes may contain a compound such as sodium carbonate that is beneficial in reducing the soil's permeability. Adequate initial testing should be conducted to determine the permeability effects of the wastes to be contained. In addition, physical factors such as freezing, thawing, drying, and wetting may affect the compacted soil liner. The compacted earth liner should be kept moist to maintain stable conditions.

SECTION 8

CHEMICAL CHARACTERIZATION OF THE INDUSTRIAL WASTES

This section attempts to describe the basic chemical components, and in some cases the origins, of the seven industrial waste categories of interest. The principal sources of this information were various EPA reports, including their water quality effluent guideline documents. In a number of instances, complete characterization of an industrial waste category in terms of chemical components and concentrations could not be determined, or a category was sometimes identified only in such terms as BOD₅, COD, TOC, and TSS. It would have been desirable to supply information concerning the primary chemical constituents of each industrial waste category, including possible toxic and hazardous materials as well as a complete description of the carrier fluids (i.e., acidic, basic, or neutral, and aqueous or organic). However, the information that was available formed the basis for the subsequent engineering evaluations and recommendations as to the suitability of the liner materials for containing specific and representative industrial wastes. These evaluations also include predictions as to the preferential liner material(s) for a given situation, and they are based on the best chemical characterization data available.

CAUSTIC PETROLEUM SLUDGE

Caustic (5.7 wt % sodium hydroxide) solutions are widely used in the petroleum refineries in such process operations as washing, sweetening, and neutralizing. Sources of spent caustic solutions are the alkylation and isomerization units, LPG treating, and Merox prewash, extraction, and sweetening. Various intermittent caustics are derived from processes such as hydrotreating, hydrocracking, and hydrosaturation. These spent caustic solutions typically contain 6.2% to 7.4% solids, of which approximately 40% to 50% is caustic. Table 19 describes the chemical constituents and compositions of the spent caustic waste streams from the various identified refinery processes. These solutions may also contain hydrocarbon materials.

OILY REFINERY SLUDGE

Oily refinery sludges are generally described as oily solids consisting of finely divided particles (which may or may not exhibit suspension characteristics) contained in aqueous streams. In addition to oil and water, such sludges are composed of sand and silt that accompany the crude oils into the refinery, other materials such as heavy metals and organics, and

TABLE 19. CAUSTIC PETROLEUM SLUDGE SOURCES AND COMPOSITION

Caustic Source	Spent Caustic Composition, wt %									
	NaOH	Mercaptides	Sulfides	Sulfites	Sulfates	Thiosulfates	Carbonates	Other		
Continuous Caustics										
Alkylation Unit	2.7	0.1	Trace	3.1	3.1	Trace	1.2	HC 0.1		
Izomerization Unit	2.7	Trace	Trace	--	--	--	1.0	NaCl, 3.9		
LPG Treating	2.7	1.0	2.2	Trace	Trace	--	1.0	--		
Mercox Prewash	2.7	0.2	3.2	Trace	Trace	Trace	1.0	--		
Mercox Extraction	24.6	Trace	Trace	Trace	Trace	0.9	1.0	Disulfides, Mercox catalyst		
Mercox Sweetening	5.2	Trace	Trace	Trace	Trace	0.6	1.0	Disulfides, Mercox catalyst		
Intermittent Caustics										
Hydrorefiner*	0.12	Trace	Trace	1.1	0.01	Trace	2.0	#		
Hydrocracker	0.12	Trace	Trace	1.1	0.01	Trace	2.0	#		
Hydro-saturator	0.12	Trace	Trace	1.1	0.01	Trace	2.0	--		

*Average of once per year for a 5-day period.

#NaNO₃, 0.13

Co, Sat

NH₃, Sat

NaCN, Trace

COS, Trace

corrosion-erosion products that result from various refinery operations. Table 20 lists the concentration ranges and total quantities of components of refinery solid wastes from a number of sources.

ACIDIC STEEL-PICKLING WASTE

In a typical steel mill, acidic wastes result from pickling lines that remove the scale formed in the steel rolling process. In the production of cold reduced steel, all scale must be removed to prevent lack of uniformity and to eliminate surface irregularities. The pickling line generally consists of several acid-proof tanks operated in series. Following the acid tanks are cold- and warm-water rinsing tanks. The first rinse washes the acid from the steel, and the second warms the steel and produces flash-drying before recoiling. The type and concentration of acid used vary according to the type and grade of steel being processed. Wastewaters from the continuous picklers originate as tank overflow, rinse sprays, scrubber flow, and looping pit discharges. Tables 21 and 22 describe the analytical data from the scrubber flow and tank overflow from a typical steel pickling line. Total discharges from the entire pickling operation of a typical steel mill may be in excess of 3.5 mgd. These wastes are dumped at times while still at elevated temperatures.

HEAVY-METAL-BEARING ELECTROPLATING SLUDGE

For the purpose of this study, heavy-metal-bearing electroplating sludge is defined as the waste that results when metallic coatings are applied on surfaces by electrodeposition. The industrial segment involved includes both independent (job) platers and captive operations associated with produce fabrication and assembly.

Waterborne wastes generated in the electroplating and metal finishing industry generally include:

- Rinse waters from plating, cleaning, and other surface-finishing operations.
- Concentrated plating and finishing baths that are intentionally or accidentally discharged.
- Wastes from plant or equipment cleanup.
- Sludges, filter cakes, etc. produced by naturally occurring deposition in operating baths or by intentional precipitation in the purification of operating baths and chemical rinsing circuits.
- Regenerants from ion exchange units.
- Vent scrubber waters.

Much of the literature on volume and composition of electroplating and metal finishing waste refers to the large or intermediate-size plants that do routine plating (Tables 23 and 24). The values shown in Table 24 are for combined raw waste effluent, and the concentrations listed are considered representative of water use in the average electroplating facility.

TABLE 20. RANGES OF CONCENTRATIONS AND TOTAL QUANTITIES FOR REFINERY SOLID WASTE SOURCES
(ALL VALUES IN MILLIGRAM PER KILOGRAM EXCEPT WHERE NOTED)

Parameters	Sludge from Clarified Once Through Cooling Water	Exchange Bundle Clearing Sludge	Slop Oil Emulsion Solids	Cooling Tower Sludge	API/Primary Clarifier-Separator Bottom	Dissolved Air Flotation Float	Kerosene Filter Clays	Lube Oil Filter Clays	Waste Biosludge
Phenols	0.0-2.1	8-18.5	5.7-68	0.6-7.0	3.8-156.7	3.0-210	2.0-25.2	0.05-6.4	1.7-10.2
Cyanide	0.01-0.74	0.0004-3.3	0-4.6	0-14	0-43.8	0.01-1.1	Trace	0.01-0.22	0-19.5
Selenium (Se)	0.1-1.7	2.4-52	0.1-6.7	0-2.4	0-7.6	0.1-4.2	0.01-26.1	0.1-2.1	0.01-5.4
Arsenic (As)	0.1-18	10.2-11	2.5-23.5	0.7-21	0.1-32	0.1-10.5	0.09-14	0.05-1.4	1.0-0.6
Mercury (Hg)	0.42-1.34	0.14-3.6	0-12.2	0-0.1	0.04-7.2	0.07-0.89	0-0.05	0.04-0.33	0-1.28
Beryllium (Be)	0.013-0.63	0.05-0.34	0-0.5	Trace	0-0.43	0-0.25	0.025-0.35	0.025-0.5	Trace
Vanadium (V)	15-57	0.7-50	0.12-75	0.12-42	0.5-48.5	0.05-0.1	13.2-42	0.3-65	0.12-5
Chromium (Cr)	16.6-103	310-311	0.1-1325	181-1750	0.1-6790	2.8-260	0.9-25.8	1.3-45	0.05-475
Cobalt (Co)	5.5-11.2	0.2-30	0.1-82.5	0.38-7	0.1-26.2	0.13-85.2	0.4-2.3	1.3-5	0.05-1.4
Nickel (Ni)	20.5-39	61-170	2.5-288	0.25-50	0.25-150.4	0.025-15	0.025-15	0.25-22	0.013-11.3
Copper (Cu)	56-180	67-75	8.5-111.5	49-363	2.5-550	0.05-21.3	0.4-12.328	0.5-8.0	1.5-11.5
Zinc (Zn)	93-233	91-297	60-656	118-1,100	25-6,596	10-1,825	6.6-35	0.5-115	3.3-225
Silver (Ag)	0.84-1.3	Trace	0-20.1	0.01-1.6	0.03-3	0-2.8	0.02-0.7	0.013-1.0	0.1-0.5
Cadmium (Cd)	0-1.0	1.0-1.5	0.025-0.19	0.06-0.6	0.024-2.0	0-0.5	0.19-0.4	0.025-1.5	0.16-0.54
Lead (Pb)	17.2-138	0.5-155	0.25-380	1.2-89	0.25-83	2.3-1,320	4.25-12	0.25-2.3	1.2-17
Molybdenum (Mo)	0.5-33	1.0-12	0.25-30	0.25-2.5	0.25-60	0.025-2.5	0.012-8.8	0.025-0.05	0.25-2.5
Ammonium Salts (as NH ₄ ⁺)	0.01-13	5-11	0-44	0.07-14	0.05-24	8.7-52	0.01	2-4	28-30
Benz-a-pyrene	0-1.8	0.7-3.6	0-0.01	0-0.8	0-3.7	0-1.75	1.7-1.8	0.02-0.2	Trace
Oil (wt.%)	0.24-17.0	8-13	23-62	0.07-4.0	3.0-51.3	2.4-16.9	0.7-5.6	0.3-9	0.01-0.53
Total Weight Metric Tons/yr.	9.7-18.0	0.4-1.0	1.4-29.2	0.1-0.13	0.3-45	13.6-31.0	0.79-127	102-682	1.8-38.5

TABLE 20 (continued)

Parameters	Coke Fines	Silt from Storm Water Run off	Leaded Tank Bottoms	Non-Leaded Product Tank Bottoms	Neutralized HF Alkylation Sludge (CaF ₂)	Crude Tank Bottoms	Spent Line from Boiler Feedwater Treatment	Fluid Catalytic Cracker Catalyst Fines
Phenols	0.4-2.7	6.3-13.3	2.1-250	1.7-1.8	3.2-15.4	6.1-37.8	0.05-3.6	0.3-10.5
Cyanide	Trace	0.48-0.95	Trace	0-14.7	0.21-4.6	0.01-0.04	0-1.28	0.01-1.44
Selenium (Se)	0.01-1.6	1.1-2.2	0.1-3.1	1.5-22.4	0.1-1.7	5.8-53	0.01-9.2	0.01-1.4
Arsenic (As)	0.2-10.8	1.0-10	63-455	Trace	0.05-4.5	5.8-53	0.05-2.3	0.05-4.0
Mercury (Hg)	0-0.2	0.23-0.36	0.11-0.94	0.41-0.04	0.03-0.09	0.07-1.53	0-0.5	0-0.16
Beryllium (Be)	0-0.2	Trace	Trace	0.025-0.49	0.012-0.13	Trace	Trace	0.025-1.4
Vanadium (V)	400-3,500	25-112	1.0-9.8	9.1-34.6	0.25-5	0.5-62	0-31.6	74.4-1,24
Chromium (Cr)	0.02-7.5	32.5-644	9.0-13.7	12.7-13.1	0.73-5	1.9-75	0.025-27.9	12.3-190
Cobalt (Co)	0.2-9.2	11.0-11.3	26.5-71	5.9-8.2	0-3-0.7	3.8-37	0-1.3	0.25-37
Nickel (Ni)	350-2,200	30-129	235-392	12.4-41	7.4-103	12.8-125	0.13-26.2	47.5-950
Copper (Cu)	3.5-5.0	14.8-41.8	110-172	6.2-164	2.5-26	18.5-194	0.22-63.2	4.1-336
Zinc (Zn)	0.2-20	60-396	1190-17,000	29.7-541	7.5-8.6	22.8-425	2.0-70	19-170
Silver (Ag)	0.01-3.0	0.4-0.6	0.05-1.7	0.5-0.7	0.12-0.25	0.03-1.3	0.05-0.7	0.5-8.0
Cadmium (Cd)	0.015-2	0.1-0.4	4.5-8.1	0.25-0.4	0.012-0.12	0.025-0.42	0-1.3	0-0.5
Lead (Pb)	0.5-29	20.5-86	158-1,100	12.1-37.3	4.5-9.6	10.9-258	0.01-7.3	10-274
Molybdenum (Mo)	0.1-2.5	6.3-7.5	0.5-118	0.25-18.2	Trace	0.025-95	0-0.05	0.5-21
Ammonium	No value	1.0	No value	0.2	Trace	2.0	Trace	No value
Salts (as NH ₄ ⁺)	Trace	0.03-2.5	0.02-0.4	0.3-0.9	No value	0-0.6	Trace	0-1.0
Benz-a-pyrene	0-1.3	2.2-5.5	18.9-21	45.1-83.2	6.7-7.1	21-83.6	0.04-0.5	0.01-0.8
Oil (wt.%)	0.06-4.2	2.7	0.2-1.3	34.7-77	28-67	0.14-0.26	28.5-214.7	0.65-23.6
Total Weight Metric Tons								

TABLE 21. PICKLE LINE SCRUBBER DISCHARGE (235,000 gpd)

Parameter	High, ppm	Low, ppm	Average, ppm
pH	3.1	1.6	2.2
Mineral Acidity	2,060.0	80.0	945.0
Total Acidity	5,720.0	140.0	2,220.0
Chlorides	4,350.0	200.0	1,600.0
Total Iron	3,266.0	32.6	760.0

TABLE 22. PICKLER TANK OVERFLOW (8.33×10^4 kl/day)

Parameter	High, ppm	Low, ppm	Average, ppm
Mineral Acidity	12,759	7,192	8,778
Chlorides	218,000	170,000	193,666
Total Solids	406,554	283,580	349,835
Suspended Solids	598	65	315
Total Iron	155,775	110,510	137,154

TABLE 23. CHROMIUM- AND CYANIDE-BEARING WASTES FROM TYPICAL PLATING
OPERATIONS IN THE ELECTROPLATING INDUSTRY*

Type of Work Plated	Chromium-bearing waste				Cyanide-bearing waste				
	Volume (mgd)	Concentration (mg/l)			Volume (mgd)	Concentration (mg/l)			
		Cr	Ni	Cu		CN	Cu	Zn	Cd
Aircraft Engines and Parts	0.440	#	#	#	0.294	#	#	#	#
Automobile Bumpers	.480	--	--	--	--	--	--	--	--
Automobile Grills	.100	700	--	--	--	--	--	--	--
Missile Parts	.080	1	--	--	.032	80	--	--	--
Office Furniture	.024	--	--	--	--	--	--	--	--
Typewriters and Office Machines	.050	16	39	--	--	39	--	--	--
Instrumentation and Control Equipment	--	--	--	--	.013	--	--	--	--
Electronic Hardware	.828	--	--	--	.259	200-1500	--	--	--
Home Appliances	.043	--	--	--	.108	--	--	--	--
Television Antennas	--	--	--	--	.011	--	--	--	--
Silverware	.040	5	33	135	.165	172	18	11	--
Instrument Motors and Electric Clocks	.112	--	--	--	--	--	--	--	--
Automobile Manufacture	.620	30	80	70	.410	204	--	113	--
Metal Fasteners	.089	52	302	--	--	--	--	--	--
Unspecified	--	--	--	--	.250	40-130	--	--	--

*Adapted from Reference 30.

#Analysis not available.

TABLE 24. APPROXIMATE CONCENTRATIONS OF WASTEWATER CONSTITUENTS
PRIOR TO AND AFTER TREATMENT FROM A TYPICAL FACILITY ELECTRO-
PLATING COPPER, NICKEL, CHROMIUM, AND ZINC³¹

Wastewater Constituent	Estimated Untreated Wastewater Concentration, mg/l	Analysis of Treated Effluent Concentration, mg/l	Water Supply Analysis, mg/l
Copper (Cu ⁺) or (Cu ²⁺)	6.7	0.23	--
Nickel (Ni ²⁺)	2.4	0.20	--
Chromium (Cr ³⁺)	0.05	0.15	--
(Cr ⁶⁺)	17	0.05	--
(Cr _T)*	17	0.20	--
Zinc (Zn ²⁺)	32	0.1	--
Cyanide	50	0.21	--
Sodium (Na ⁺)	465	--	20
Potassium (K ⁺)	2.4	--	--
Carbonate (CO ₃ ²⁻)	57	--	--
Orthophosphate (PO ₄ ³⁻)	47	3.0	0.01
Pyrophosphate (P ₂ O ₇ ⁴⁻)	53	--	--
Silicate (SiO ₃ ²⁻)	50	--	--
Metaborate (BO ₂ ³⁻)	36	--	--
Perborate (BO ₃ ³⁻)	1.3	--	--
Sulfate (SO ₄ ²⁻)	19	--	20
Bisulfate (HSO ₄ ⁻)	3.7	--	--
Fluoride (F ⁻)	0.1	--	0.1
Fluorosilicate (SiF ₆ ²⁻)	0.5	--	--
Tartrate (C ₄ H ₄ O ₆ ²⁻)	8.9	--	--
Chloride (Cl ⁻)	228	--	25
Nitrate (NO ₃ ⁻)	1.4	--	--
Wetting agents (organic)	6.8	--	--
Sequestrants	6.5	--	--
Chelates	6.5	--	--
Additives (organic)	0.5	--	--
Proprietary acid salts	32	--	--
Total dissolved solids	1150.0	--	--

*(Cr_T=Total Chromium)

TOXIC PESTICIDE FORMULATION WASTE

Pesticide formulations are generally classified as liquids, granules, dusts, or powders. Most pesticides are mixed in equipment used only for that purpose. The most important unit operations involved are dry mixing and grinding of solids, dissolving of solids, and blending. The major source of contaminated wastewater from such plants is the periodic cleanup of formulation lines (including filling equipment), which is carried out to prevent cross-contamination of one product with another. Liquid formulation lines are cleaned out most frequently, and they generally require the most water. Liquid washouts are generally required, but only in those sections of the units where liquids are normally present (i.e., the active ingredient pumping system, scales, and lines). The remainder of the formulation unit can normally be cleaned out by dry washing with an inert material such as clay.

In addition to cleanup of formulation equipment, the principal sources of wastewater generated at pesticide formulator and packaging plants are spill washdown, drum washing, air pollution control devices, and area runoff (Table 25). Note that the concentrations of these wastewater contaminants have been reported only in such terms as COD, BOD₅, TSS, TOC, and TDS.³⁰

TOXIC PHARMACEUTICAL WASTE

The major sources of wastewater in the pharmaceutical industry are by-product washings, the extraction and concentration of byproducts, and equipment washdown. The wastewaters are generally characterized³⁰ as containing high concentrations of BOD, COD, TSS, and solvents. Wastewaters from some chemical synthesizing and fermentation operations may contain metals (Fe, Cu, Ni, Ag, etc.), cyanide, or antibacterial constituents.

Wastes from the pharmaceutical industry may also originate from the following general processing categories:

- Fermentation. Used primarily to produce antibiotics and steroids from batch fermentation tanks in the presence of a particular fungus or bacterium.
- Biological products and natural extractive manufacturing. Used to produce blood derivatives, vaccines, serums, animal bile derivatives, and plant tissue derivatives.
- Chemical synthesis. Used to produce hundreds of products, from vitamins to antidepressants.
- Formulation. Used to convert the products of the other three manufacturing areas into final dosage forms (tablets, liquids, capsules, etc.) marketed to the public.
- Research. Includes microbiological, biological, and chemical activities.

Wastewaters generated by the fermentation and chemical synthesizing processes contain much higher pollutant concentrations than those resulting from the manufacture of biological and natural extraction products. An analysis of raw waste loads by processing category is given in Table 26.

TABLE 25. SUMMARY OF POTENTIAL PROCESS-ASSOCIATED WASTEWATER
SOURCES FROM PESTICIDE FORMULATORS AND PACKAGERS³²

Processing Unit	Source	Nature of Wastewater Contaminants
Mix tank	Condensate from equipment steam cleaning	Dissolved organics and suspended and dissolved solids. Noncontinuous flow rate and relatively low flow. pH variable.
Air pollution control equipment	Scrubber water	High in suspended and dissolved solids and dissolved organics. Relatively low flow rate.
Drum washers	Rinse water, floor drains, and caustic solution	Dissolved organics and suspended and dissolved solids. High pH.
Formulation lines and filling equipment	Wash water and steam condensate from clean out	Dissolved organics and suspended and dissolved solids. A major source of wastewater.
All product formulation and blending areas	Area washdown and clean-up water, spills, leaks	Dissolved organics and suspended and dissolved solids.
Warehouse, technical active ingredient storage	Spills, leaks, run-off	Dissolved organics and suspended and dissolved solids.

TABLE 26. RAW WASTE CONSTITUENTS FROM THE PHARMACEUTICAL INDUSTRY³² (kg/kg production*)

Process	TDS	NO ₃ -N	Oil		Cl	SO ₄	Sulfide	Total		Ca	Mg	Cu	Phenol
			Total	and Grease				Hard-	ness				
Fermentation	5.990	4.68	22.0	413	1.260	274	#	294	123	30	0.005	0.15	
Biological Products and Natural Extractive													
Manufacturing	895	0.02	7.3	3.62	211	277	#	--	36.4	--	0.12	0.073	
Chemical													
Synthesis	1.060	0.20	7.83	21.6	104	203	--	61.6	15.2	5.68	0.002	0.16	
Formulation	11.3	0.053	0.15	0.78	2.51	0.52	0.007	5.82	1.01	--	0.001	--	
Research	1.33	Trace	0.23	#	0.94	1.27	#	--	--	--	--	--	

*English equivalent would be lb/1,000 lb production.

#Data not reported.

WASTES FROM RUBBER AND PLASTICS INDUSTRIES

For the purpose of this study, the plastics industry is defined as companies involved in the production of epoxies, melamines, ureas, and phenolics. The rubber industry consists of the tire and inner tube industry and the synthetic rubber industry.

Information concerning flow rates and compositions of process wastewater streams associated with the plastics industry is severely limited, and the best available is expressed only in terms of BOD₅, COD, and suspended solids.³¹ The following are the essential elements, compounds, and parameters considered to be important constituents of the process waste streams:

pH	Chromium
Color	Copper
Turbidity	Lead
Alkalinity	Zinc
Temperature	Iron
Nitrogenous compounds	Cobalt
(organic, amines, and nitrates)	Cadmium
Oils and greases	Manganese
Dissolved solids	Aluminum
(principally inorganic chemicals)	Magnesium
Phosphates	Molybdenum
Phenolic compounds	Nickel
Sulfides	Vanadium
Cyanides	Antimony
Fluorides	Numerous organic chemicals
Mercury	

Process wastewaters from the tire and inner tube industry include discharges of solutions used in the manufacturing process, washdown of processing areas, run-off from raw material storage areas, and spills and leaks of cooling water, steam, processing solutions, organic solvents, and lubricating oils. Primary pollutants in these wastewaters are oil, grease, suspended solids, and acidity and alkalinity (pH).

The synthetic rubber industry generates wastewaters that contain the same general constituents described above. The significant waste components are COD, BOD, suspended solids, dissolved solids, and oil and grease.³² Heavy metals, cyanides, and phenols are not generally found in significant quantities (less than 0.1 mg/liter) in synthetic rubber process wastewaters.

SECTION 9

COMPATIBILITY OF LINER MATERIALS AND INDUSTRIAL WASTES

The information presented in this report forms the basis for the following evaluations of liner material suitability for containing specific and representative industrial wastes. The prediction of liner/industrial waste compatibilities found in Table 1 are, of course, based on the best available chemical characterization data. In a number of instances, this information has been incomplete or presented in terms such as BOD₅ and COD, which are not adequate for making such predictions.

The chemical resistance of a material refers to its ability to withstand two primary types of chemical attack--actual reaction with chemicals, and absorption of chemicals. A liner material with good resistance to a particular chemical will neither react readily with nor absorb the chemical significantly while in contact with it. If a liner material has poor resistance to a particular chemical, reaction with or absorption of it will occur with concurrent loss in the physical properties of the liner. Failure of the liner material may follow.

Thus the selection of a liner material for an impoundment site must begin with an in-depth characterization of the industrial waste that will be contained. Such a study should include identification of the chemical components and their respective concentrations.

Final selection of the liner material should also include laboratory determination of the effects that a specific industrial waste has on the liner material. The resistance of a lining material to chemical attack by a waste can be assessed by immersing specimens of the liner in the waste and observing changes in physical properties as a function of immersion time, following procedures specified in standard tests such as ASTM Method D471. Liner specimens can be subjected to long-term exposure tests at lower temperatures or accelerated tests at elevated temperatures. The more closely the exposure conditions simulate actual service, the more reliable the results will be. Therefore, long-term exposure tests (e.g., 12 months) at room temperature should give better results than shorter tests at higher temperatures, though there may still be some question as to correlation of laboratory testing with service performance.

Table 1 indicates that there are currently available materials suitable for containing any of the seven categories of industrial waste discussed. The ratings of "good," "fair," and "poor" for the compatibility of given combinations were determined by considering the available information on chemical

components of the industrial waste with the chemical resistance data for the liner materials (as listed in Tables 2 through 9 and 12 and discussed in Sections 4 and 7). The "good" rating indicates that satisfactory service of the liner material in the industrial waste will be obtained. A "fair" rating indicates that the liner material is suitable only for intermittent exposure. And a "poor" rating indicates that the liner material is not recommended for industrial waste that contains components that will chemically attack the liner and result in ultimate failure.

Caustic petroleum sludge is alkaline and contains salt components; consequently, soil cement, soil asphalt, compacted clays, and soil bentonite would be subject to attack. These lining materials are therefore rated "fair," as this waste stream may also contain hydrocarbons. All of the asphalt lining materials and all of the membrane linings, except possibly polyethylene and polypropylene, must be rated "fair." If no hydrocarbon is present in the waste, all the membranes are satisfactory as well as asphalt membrane and concrete.

Oily refinery sludge contains even higher concentrations of hydrocarbons (Table 20), along with quantities of phenol and heavy metals. But the salt concentrations and alkalinity are very low. On the basis of this information, only oil-resistant PVC, polyethylene, polypropylene, soil cement, soil bentonite, and compacted clays are judged to be acceptable from a chemical resistance point of view.

Acidic steel pickling wastes are high in acidity (low pH) and salt content (Table 21). Therefore the linings based on soil and clay, including bentonite, are rated "poor." In addition, because this waste is sometimes introduced into ponds at elevated temperatures, asphalt membranes and polymeric membranes such as PVC, polyethylene, polypropylene, and CPE are rated "poor." Rubber membranes and chlorosulfonated polyethylenes are rated "good."

Heavy-metal-bearing electroplating sludges generally contain high salt concentrations and small amounts of organic additives. Consequently, lining materials based on soils and clays, including bentonite, are rated "poor." The asphalt materials (i.e. the membranes and concretes) are rated "fair," as are the thermoplastic membranes, PVC, polyethylene, and chlorinated polyethylene. The rubber, butyl, EPDM, polypropylene, and chlorosulfonated polyethylene are rated "good."

Although the information on toxic pesticide formulation wastes did not identify the concentrations of organic components, they were assumed to be on occasion at least 25 wt %. On this basis, oil-resistant PVC, polyethylene, polypropylene, soil cement, soil bentonite, and compacted clays are rated "good." Because of the possibility of organic chemical components in this waste, the other liners are rated "fair."

The rationale for toxic pharmaceutical wastes followed similar lines. The information on concentrations of organic constituents was limited, but the types and quantities of such materials were assumed to be greater than those found in toxic pesticide formulation wastes. Hence, only oil-resistant PVC, soil cement, soil bentonite, and compacted clays were rated "good."

Since the primary pollutants in the waste streams from the rubber and plastics industries were described^{31,32} as oil, grease, suspended solids, acidity, and alkalinity, it was assumed that the concentrations of these materials were less than 0.1 mg/liter. On this basis, all lining materials are rated "good" for this waste stream.

In all cases, final selection of the liner material should be based on the additional parameters discussed throughout the report, particularly in Section 2. Final selection should also be based on laboratory immersion tests (preferably long-term) of the liner material in the industrial waste to be contained.

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APPENDICES

APPENDIX A. NEW POND/PIT LINER SYSTEM

DuPont Co. has recently introduced an entirely new system for lining industrial, agricultural, and municipal ponds and pits.* The 3110 liner system reportedly marks the first time that portable, hand-held welding equipment has been made available for liner installations. Designed specifically for use with a proprietary elasticized polyolefin sheeting, the welding unit produces reliable and economical field seams at rates up to 6.1 m/min (20 ft/min), depending on ambient temperatures. DuPont also claims that by using the welder, acceptable heat seams 1.9 cm (3/4 in.) wide can be made in continuous lengths, even when weather conditions make other field seaming methods inadequate.

The seamless polyolefin sheeting, furnished in rolls 6.1 m wide, 61.0 m long, and 0.051 cm thick (20 ft x 200 ft x 0.020 in.) is wide enough to eliminate factory fabrication into large panels. DuPont also maintains that because the sheeting is resistant to ultraviolet light, it does not require a covering of earth for protection.

* Anon. Chemical Engineering, 60, April 1975.

APPENDIX B. MANUFACTURERS, FABRICATORS, SUPPLIERS, AND INSTALLERS
OF LINER MATERIALS*

1. Hodgman Division
Plymouth Rubber Co., Inc.
104 Revene Street
Canton, MA 02021
(617) 828-0875
(212) 594-0240
Mr. Charles Nees
Mr. Kevin Doolin
2. Unit Liner Company
P.O. Drawer 1460
Wewoka, OK 74884
(405) 257-3323
Mr. J. A. Hendershot
3. Watersaver Company, Inc.
3560 Wynkoop Street
Denver, CO 80216
(303) 623-4111
Mr. C. J. Gerker
Mr. W. Slifer
4. Goodyear Tire and Rubber Co.
1210 Massillon Road
Akron, OH 44306
(216) 794-4002
5. Carlisle Tire and Rubber Co.
Carlisle, PA 17013
(717) 249-1000
Mr. Hugh C. Kenny
Mr. Ray Jumper
6. Staff Industries, Inc.
78 Dryden Road
Upper Montclair, NJ 07043
(201) 744-5367
Dr. Charles Staff
7. Fabrico Mfg. Corp.
1300 W. Exchange Ave.
Chicago, IL 60609
(312) 254-4211
8. Burke Rubber Company
2250 South 10th Street
San Jose, CA 95112
(408) 297-3500
9. Reeves Bro., Inc.
P.O. Box 431
Rutherfordton, NC 28139
(704) 286-9126
Mr. Walter A. McEvilly
10. Dow Chemical Co.
Park 80 Plaza East
Saddle Brook, NJ 07662
(201) 845-5000
Mr. Robert Woodshire
11. B. F. Goodrich Company
500 South Main Street
Akron, OH 44318
(216) 379-3565
Mr. F. Long

* Compiled during the course of the commercial literature review.

12. E. I. DuPont Co.
3707 Chevy Chase
Louisville, KY 40218
Mr. Gerry Fisher

E.I. DuPont Nemours & Co.
Bank of Delaware, Suite 724
Wilmington, DE 19898
Mr. F.J. Rizzo (added May 1978)
13. Dowell
Div. of Dow Chemical Co.
140 Concord Street
Indiana, PA 15701
Mr. Thomas A. Sutton
14. Key Enterprises
Odessa, TX
15. St. Clair Rubber Co.
1765 Michigan Avenue
Marysville, MI 48040
(313) 364-7424
Mr. John J. Arcuri, Jr.
16. Gulf Seal Corporation
410 Main Building
Houston, TX
Mr. John Saenz
17. Misco United Supply Co.
257 N. Broadway
Wichita, KS 67202
18. Gulf States Asphalt Co.
610 Jefferson Street
Houston, TX 77002
19. Chemprene
Beacon, NY
- (914) 831-2800
Mr. Spicer
20. Plasti-Steel, Inc.
Vickers KSB and T Bld.
Wichita, KS 67202
(316) 262-6361
21. Liberty Vinyl Corporation
3380 Edward Avenue
Santa Clara, CA 95050
(408) 249-1234
Mr. Roy Lambert
22. Revere Plastics, Inc.
Little Ferry, NJ
(201) 641-0777
23. Hovater-Way Engineers, Inc.
1833 E. 17th Street
Santa Ana, CA 92701
(714) 835-8124
24. Hartwell Company
740 Albert Avenue
Lakewood, NJ 08701
Mr. Jack Hartwell
25. American Colloid Company
5100 Suffield Court
Skokie, IL 60076
26. The Pantasote Co. of New York, Inc.
26 Jefferson St.
Passaic, NJ 07055 (added May 1978)
27. Schlegel Area Sealing Systems, Inc.
P.O. Box 197
1555 Jefferson Rd.
Rochester, NY 14601 (added May 1978)

APPENDIX C. LISTS OF CASE HISTORIES OF LANDFILL IMPOUNDMENT SITES*

TABLE C-1. INSTALLATIONS IDENTIFIED DURING COURSE OF LITERATURE REVIEW AND FROM PERSONAL COMMUNICATIONS WITH INSTALLERS, FABRICATORS, ETC.

Liner Material and Date Installed	Industrial Waste	Installer	Lagoon Owner
1) Hypalon	Acidic steel- pickling waste		Imperial West Chemical Co. Antioch, CA D. A. Huckabay, Pres.
2) Nylon/Butyl (1973)	Textile finishing wastes		Reeves Bro., Inc. Bishopville, SC
3) Hypalon (1969)	Brine or crude oil	Unit Liner Co. Wewoka, OK	Mid America Pipeline Co. Conway, KS
4) PVC	22 acre aeration lagoon for pulp and paperboard wastes	Staff Industries and Cornell, Howland, Haynes or Merryfield (enrg. firm)	Weyerhaeuser Company Springfield, OR
5) Soil Sealant (Dowell-Dow Chem) (1971- 72)	Steel plant process water		Penna, WV
6) Soil Sealant (12/72)	Oil-contaminated fresh water		Tulsa, OK
7) Asphalt and Polypropylene Fiber Mat (Petromat*) (Phillips Pet. Co.) (Nov. 1969)	Oil refinery wastewater	Litwin Corp. Wichita, KS	Tesoro Alaskan Petro- leum Corp. Alaska

TABLE C-1 (continued)

Liner Material and Date Installed	Industrial Waste	Installer	Lagoon Owner
8) Asphalt	Dye wastes	Burns Construction Co., Las Cruces, NM and Gulf Seal Corp., Houston, TX	Hanes Corp. Mesilla, NM
9) Soil Cement (1972)	Combination of municipal and industrial wastes (paper mill)	Holloway Construction Co., Lansing, MI	Muskegon, MI County Dept. of Public Works
10) Soil-Bentonite (Hypalon-covered Slopes) 5-Acre Lagoon	Electroplating wastes	Staff Industries and local contractor	Rockwell, Int. Newton Falls, OH
11) PVC (20 mil) (1970)	Brine evaporation ponds		Texasgulf, Inc. Moab, UT
12) Polyethylene	Caustic waste of olive processing industry (8 ponds- 205 total acres)		Lindsay, CA

TABLE C-2. CASE HISTORIES OF DOWELL SOIL SEALANTS*

Customer	Location	Type of Pond	Stored Fluid	Date
Village	Parma, Michigan	2 sewage lagoons	sewage water	Oct. 1971
City	Monahans, Texas	recreational pond	fresh water	Mar. 1972
Lost Lake Country Club	Ossinlike, Michigan	sewage lagoons	sewage water	Aug. 1972
Oil Refinery	Tulsa, Oklahoma	storm water collection pond	oil contaminated fresh water	Dec. 1972
Village	Roscommon, Michigan	sewage lagoon	sewage water	Nov. 1973
Paper Company	Baton Rouge, Louisiana	industrial retention pond	plant water	Sept. 1970
Oil Company	Granby, Colorado	recreational lake	fresh water	May 1969
Steel Corporation	Pennsylvania, W. Virginia	industrial ponds	process waters	1971-1972
Uranium Mining Company	Grants, New Mexico	settling pond	mine waters	1969
Copper Mining Corporation	Arizona	tailings dam	fresh water	Apr. 1972
Natural Gas Producer	New Mexico	retention pond	brackish waters	May 1973

*Commercial literature of Dowell, Division of the Dow Chemical Company, Tulsa, Oklahoma 74102.

TABLE C-3. PARTIAL LIST OF CASE HISTORIES OF ASPHALT-LINED
LAGOONS AND TREATMENT AREAS*

Type of Treatment Area	Location and Description
Sewage Holding Ponds	Velders, Reedsville, Sister Bay, Chippewa Falls (all in Wisconsin); 2 to 3 in. asphalt concrete.
Brine Storage Reservoirs	Eldorado, Arkansas (Michigan Chemical, McAlester Fuel Co., High Bank Oil Field); buried asphalt membrane.
Wastewater Lagoon	Graniteville Co., Graniteville, South Carolina; 3 in. asphalt concrete, emulsified asphalt seal.
Wastewater Lagoon	Olin Mathieson, Atlanta, Georgia; asphalt seal on asphalt concrete.
Sludge Drying Bed	Grand Rapids, Michigan; asphalt concrete.
Sewage Lagoon	Pocomoke City, Maryland; 3 in. sand asphalt.
Copper Recovery Pads	Anaconda, Butte, Montana; asphalt membrane on asphalt concrete.
Reactionary Ponds	Echo Corp., Warren, Pennsylvania.
Iron Ore Storage Lagoon	Midland Ross Corp., Portland, Oregon.
Lithium Brine Storage Pond	Foote Mineral Co., Silver Peake, Nevada; asphalt membrane on asphalt concrete.
Settlement Ponds	Sugar beet refinery, Fargo, North Dakota; asphalt concrete.
Ash Pond	New Castle, Pennsylvania; 3 in. asphalt core, 4 in. porous asphalt.

* Courtesy of the Asphalt Institute, College Park, Maryland.

APPENDIX D. SOIL CEMENT CONTRACTS FOR WATER CONTROL*

Most of the 102 soil cement contracts awarded in the period 1961-1974 were for slope protection for earth dams or other embankments. They can be classified by design and construction method, as follows (some of them involve two or more different designs):

- Design A. Embankment facing, stair-step construction, 59 projects.
- Design B. Embankment facing, stair-step construction, exposed to flowing water, 15 projects.
- Design C. Embankment facing or lining, construction in one or more layers, parallel to slope, 18 projects.
- Design D. Embankment facing or lining, construction in one or more layers, parallel to slope, exposed to flowing water, 8 projects.
- Design E. Mass placement, usually in horizontal layers, including foundations, trenches, and channels, 10 projects.

Mixing of the soil cement was generally by the central-plant process, and placement was in approximately horizontal layers with 6-in. compacted thickness.

The thickness of soil cement on the projects of Designs A or B, unless otherwise noted, was 2 to 2.5 ft. Resulting square-yard costs for those thicknesses consequently are 67% to 83% of the cubic-yard costs. When alternate designs were provided, it was usually assumed that 2 ft of soil cement would provide embankment protection equivalent to that provided by 3 ft of riprap and bedding combined.

The 102 projects required a total of 5.6 million yd³ of soil cement (Table D-1). In more than half the projects, soil cement was specified with no alternative. For three of the projects, totaling 449,000 yd³, no contractor bid the riprap alternative specified. For another 14 projects, totaling 792,000 yd³, bids were received on both soil cement and alternative materials, with the awards going to soil cement. Total savings for those 14 projects were estimated to be nearly \$3 million--an average of \$3.76/yd³.

Table D-1 indicates how the weighted average contract cost has changed from year to year. The yearly variations in weighted average should not be surprising, since the cost of soil-cement depends on the cement percentage, which is based on the characteristics of the soil aggregate available and on

* Extracted from Soil-Cement for Water Control - Contracts Awarded - Summary No. 8, December 31, 1974, Portland Cement Association, Old Orchard Road, Skokie, Illinois 60076. In this summary 102 individual projects are listed with the following information given for each: location, owner, engineer, contractor, bid date, quantity of soil cement in project, cement content, cost data, and construction period.

TABLE D-1. SOIL CEMENT FOR WATER CONTROL, SUMMARY BY YEAR

Year	Number of Contracts Awarded	Total yd Awarded	Weighted Average Cost/yd	End of Year EN-R Const. Cost Index	Adjusted Unit Cost Base = 1961
1961	1	51,000	\$8.37	855	\$8.37
1962	5	254,800	6.24	880	6.06
1963	3	159,575	6.97	915	6.51
1964	8	356,325	8.16	948	7.36
1965	7	69,100	7.22	988	6.25
1966	3	114,600	7.10	1,034	5.86
1967	11	848,575	6.04	1,098	4.70
1968	6	206,895	6.35	1,201	4.52
1969	9	241,435	6.76	1,305	4.43
1970	8	470,120	10.65	1,445	6.30
1971	9	420,330	6.51	1,672	3.31
1972	8	732,280	9.33	1,816	4.39
1973	9	671,560	10.20	1,939	4.50
1974	15	988,965	14.79	2,103	6.01
Total	102	5,585,560	---	---	---

the size and nature of the project. Only one or two unusually difficult and expensive projects in a given year can have a seriously misleading effect on the average costs. Note that the weighted average soil cement contract costs, adjusted to 1961 dollars using the EN-R Construction Cost Index, show a trend that is generally downward, with the 1974 adjusted, weighted average cost lower than that for any of the first 5 years.

The following Portland Cement Association publications on soil cement slope protection are available to residents of the United States and other countries (except Canada) from the Order Processing Department, Portland Cement Association, Old Orchard Road, Skokie, Illinois 60076. (Minimum order \$1.00. For orders under \$5.00, add 50 cents for handling and surface mail.) Residents of Canada should direct inquiries to the nearest Portland Cement Association office (Edmonton, Alberta; Halifax, Nova Scotia; Montreal, Quebec; Ottawa, Ontario; Toronto, Ontario; or Vancouver, British Columbia.)

PA074W	Soil-Cement Slope Protection for Earth Dams	\$1.20
IS126W	Soil-Cement for Paving Slopes and Lining Ditches	0.60
RD010W	Dam Construction and Facing with Soil-Cement	0.60
IS173W	Soil-Cement Slope Protection for Earth Dams: Planning and Design	0.30
IS166W	Soil-Cement Slope Protection for Earth Dams: Laboratory Tests	1.65
IS052W	Suggested Specifications for Soil-Cement Slope Protection for Earth Dams	0.15
IS167W	Soil-Cement Slope Protection for Earth Dams: Construction .	0.75
IS168W	Soil-Cement Slope Protection for Earth Dams: Field Inspection and Control	0.90
PA127W	Soil-Cement Embankment Protection for Power Plant Cooling Water Basins	0.60